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OPERATIONS PLAN FOR THE TROPICAL CYCLONE MOTION (TCM-92) MINI-FIELD EXPERIMENT

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A WC-130 instrumented aircraft will be deployed in the Western North Pacific region near Guam during 21 July-18 August 1992 to obtain in situ measurements in Mesoscale Convective Systems embedded in tropical cyclones. Four hypotheses related to different tropical cyclone track modification or genesis mechanisms will be tested. The scientific basis for these hypotheses is described and observations and models of midlatitude mesoscale convective systems are reviewed to provide a basis for planning the WC-130 missions. Aircraft operations and the Experiment Operations Center are described, along with tentative flight tracks. Descriptions of the real-time observations and the data to be archived for post-experiment analyses are provided.

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ACKNOWLEDGEMENTS

The original motivation for the TCM-92 mini-field experiment described in this report was lectures given by Dr. Hugh Willoughby of NOAA-HRD when he was in the Haltiner Research Chair at the Naval Postgraduate School. When Dr. Greg Holland of the Australian Bureau of Meteorology Research Centre and Dr. Mark Lander of the University of Guam then described their study of the Typhoon Sarah case, it was clear that *in situ* observations were required for further understanding. However, many components had to come together in the planning and preparations for TCM-92. First, the 815th Tactical Airlift Squadron WC-130 aircraft had to be available during this period. All of the 815th personnel have been very helpful in answering our inquiries. LCDR C. C. Nelson and LCOL F. Hauth (USAF, Ret.) of the Office of Federal Coordinator for Meteorology have acted as agents for our request. Second, funding was provided by Dr. R. F. Abbey, Jr., of the Office of Naval Research Marine Meteorology Program, and by the Naval Postgraduate School Direct Research Fund. Our colleagues have been very generous in sharing their ideas and advice. LCOL C. Guard, Director of the Joint Typhoon Warning Center, has been very supportive in both ideas and in making arrangements to host the Experiment Operations Center. In addition to H. Willoughby, G. Holland and M. Lander mentioned above, Professors Bill Frank and Mike Fritsch of Pennsylvania State University have shared their research results prior to publication. Professors Les Carr and Pat Harr of the Naval Postgraduate School have reviewed the plans and offered advice. Professor R. L. Haney has allowed LCDR G. Dunnavan to participate in the planning and execution of TCM-92. Mark Boothe of the Naval Postgraduate School is also participating in the planning. The Air Force Institute of Technology has funded the graduate education of CAPT E. McKinley and his air fare to Guam. Last, but not least, Mrs. Penny Jones has rapidly and accurately produced many versions of the plan.

ABSTRACT

A WC-130 instrumented aircraft will be deployed in the Western North Pacific region near Guam during 21 July - 18 August 1992 to obtain *in situ* measurements in Mesoscale Convective Systems embedded in tropical cyclones. Four hypotheses related to different tropical cyclone track modification or genesis mechanisms will be tested. The scientific basis for these hypotheses is described and observations and models of midlatitude mesoscale convective systems are reviewed to provide a basis for planning the WC-130 missions. Aircraft operations and the Experiment Operations Center are described, along with tentative flight tracks. Descriptions of the real-time observations and the data to be archived for post-experiment analyses are provided.

1. Introduction

One of the primary components of the Office of Naval Research Tropical Cyclone Motion research initiative was a major field program called Tropical Cyclone Motion (TCM-90) during August and September 1990. Elsberry (1990) describes the planning for TCM-90 in conjunction with three other field experiments sponsored by the nations of the World Meteorological Organization Typhoon Committee, the USSR and Taiwan. Elsberry *et al.* (1990) summarize the field experiment Intensive Observing Periods (IOP).

During TCM-90, considerable attention was devoted to mesoscale convective systems (MCS) in anticipating tropical cyclone formations that might become a target storm for an IOP. Since the end of TCM-90, observational and numerical modelling studies by Holland and Lander (1991) have suggested that these MCS may have a significant role in causing meanders in the tropical cyclone tracks with amplitudes of about 100 km and periods of 1-2 days. Theoretical models such as Willoughby (1991) have indicated that MCSs near the center of the tropical cyclone may cause shorter term oscillations. All of these studies were limited due to insufficient knowledge of the three-dimensional structure of the MCS that are normally revealed only in the enhanced infrared (IR) imagery.

A mini-field experiment called TCM-92 has been proposed for July-August 1991 to obtain *in situ* measurements within MCSs to provide structural information necessary to improve understanding and models of tropical cyclone motion. The scientific basis for the hypotheses that MCSs cause tropical cyclone track deviations is discussed first. Because so little information is known about the MCS in the tropics, some recent research in midlatitude MCS characteristics also is reviewed to provide a basis for planning TCM-92. The hypotheses to be tested in TCM-92 are summarized in Section 2.

The primary observation platform for TCM-92 is an Air Force Reserve WC-130 from the 815th Tactical Airlift Squadron at Keesler Air Force Base. Plans for utilizing the WC-130 in the western North Pacific are described in Section 3. Real-time data from the flights will be transmitted via a satellite communication system, which will also notify WC-130 personnel of the need to modify flight tracks for any changes in the MCS detected in hourly satellite imagery received at the Experiment Operations Center in Guam.

Funding for TCM-92 has been provided in nearly equal grants from the Office of Naval Research Marine Meteorology Program (R. F. Abbey, Jr., Program Manager) and the Naval Postgraduate School Direct Research Funding. The Office of the Federal Coordinator for Meteorology (OFCM) has kindly served as the agent for negotiations for the WC-130 deployment. At the time of this writing (end of May 1992), tentative approval for deployment of the WC-130 to the western Pacific has been received. Discussions with the Naval Oceanography Command Center/Joint Typhoon Warning Center (JTWC) to support the Experiment Operations Center are not complete. However, this draft of an operations plan for TCM-92 is being circulated to encourage the widest possible discussion and participation in this mini-field experiment. Comments are welcomed and will be incorporated in the planning as possible within the limited time and resources available.

a. Track deviations due to asymmetric convection

The idea that an asymmetric distribution of convection near the center of the tropical cyclone could cause track deviations has existed for some time (Elsberry 1987). Early support for this idea came from radar photographs during periods of trochoidal motion. That is, the center of the storm appeared to accelerate and decelerate and have

cross-track deviations on the order of the eyewall radius as regions of intense radar echoes rotated about the core. It is reasonable that an asymmetry in convective latent heat release would produce an associated isallobaric tendency with low surface pressure, and thus a perturbation on the low pressure core in the center. As this perturbation would rotate with the convection asymmetry, the minimum surface pressure that defines the storm track may also seem to follow the rotation. This combination of a rotation plus an environmental steering results in a trochoidal-type track.

Satellite imagery (Black 1987) occasionally reveals a strong asymmetry in deep convection (which Black called a "supercell") during the early stages of tropical cyclone development. In addition to modifying the intensification process, the track is deflected toward the convection asymmetry. Several researchers (Fett and Brand 1975; Lajoie and Nicholas 1974) have studied changes in tropical cyclone track directions in response to a change in orientation of the primary convection area as observed in satellite imagery. However, the empirical rules they developed have not been applied successfully in operational forecasting because of the lack of specificity about when the turning motion may occur (e.g., is it 6 h, 12 h, 18 h, etc.?). In addition, the rules did not address the ranges of asymmetric convection magnitudes, durations and separation distances that occur in nature. One might also suspect that the intensity (or other aspects of the wind structure) of the tropical cyclone would also be a factor, but this aspect was not included in the empirical rules.

Willoughby (1991) has developed a barotropic, shallow-water model of the track changes in response to a rotating mass source-sink that represents the rotating convection asymmetry just outside the radius of maximum winds. Willoughby's model does indeed produce a trochoidal track that has a period equal to the rotation period of the convection. The cross-track deflections due to this process are on the order of 10 km. Consequently, the rotating convection mechanism is compatible with the radar observations of track deviations of this magnitude. Whereas such short-term oscillations in radar center fixes may be critical near landfall, the forecaster would normally smooth these oscillations to obtain a more conservative, longer term estimate of the present and future track.

A more intriguing result from the Willoughby (1991) model is that a stationary mass source-sink pair relative to the tropical cyclone center causes a track deflection of larger magnitude that may have a persistence beyond the end of the convection asymmetry (Fig. 1). The center is deflected toward the mass sink (which represents the asymmetry in deep convection in the model) due to the divergent wind component from the source to the sink that flows across the storm center, and also interacts with the symmetric vorticity pattern. In addition, Willoughby finds the asymmetry triggers the development of a normal mode in his linear model that is in the form of a wavenumber one gyre (Fig. 2). Although the gyre circulation is damped after the mass source-sink is removed, the flow between the gyre centers continues to deflect the storm center relative to the steering as the gyre damps. Consequently, the track deflection may persist and perhaps cause a significant deviation if the asymmetry in convection was strong and sustained.

Flatau (1991) studied the response of a multi-level baroclinic model to imposed asymmetries in convective latent heat release. Whereas Willoughby only considered convection near the cyclone center, Flatau found significant track deviations were produced even when the convection was a few hundred kilometers from the center. Such a persistent convection region might exist along a feeder rainband.

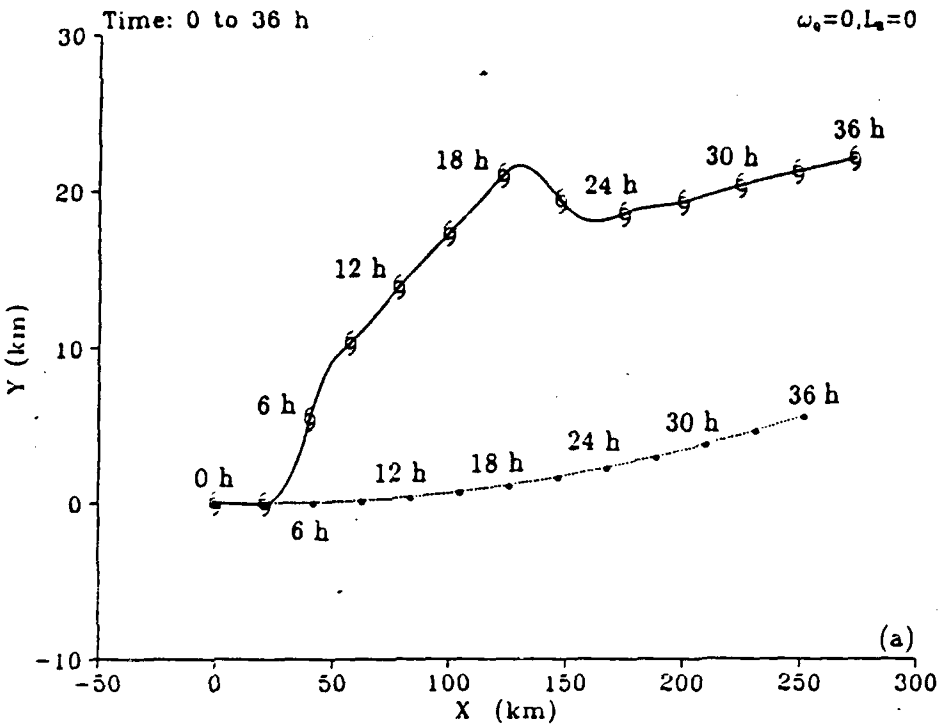

Fig. 1 Vortex tracks each 3 h with ( ) and without (dots) the inclusion of a fixed mass source-sink relative to the center of the vortex in the Willoughby (1991) barotropic model. The mass source-sink is initiated at t = 3h and terminated at t = 18 h, and the environmental flow is 2 m/s from the west.

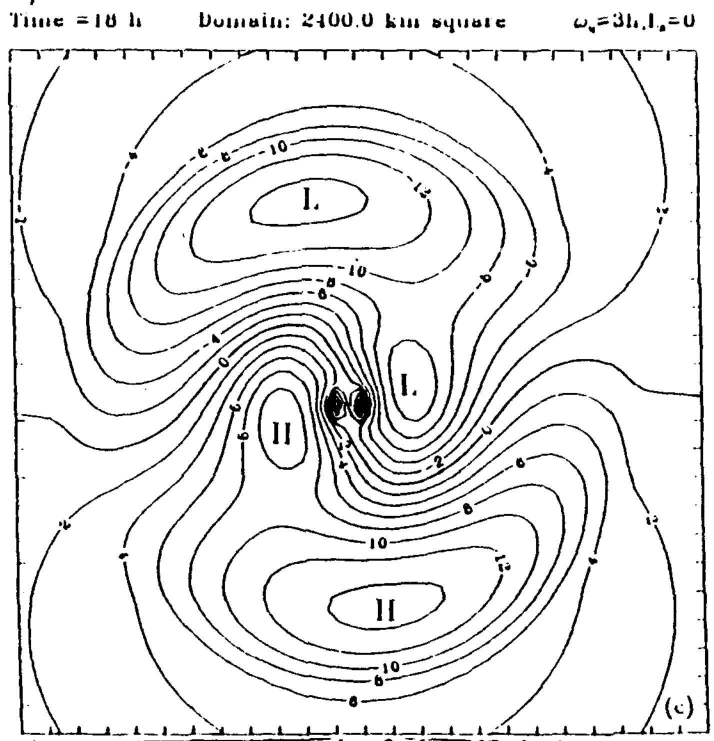

Fig. 2 Streamfunction (contour interval, 2×10^4 m^2s^{-1}) after 18 h of the integration of the Willoughby (1991) barotropic model with the inclusion of a fixed mass source-sink and an environmental flow of 2 m/s as in Fig. 1.

b. Nonlinear interaction with adjacent mesoscale convective complex

Holland and Lander (1991) have examined "meanders" in tropical cyclone tracks on time scales of hours (e.g., the radar-observed track oscillations) to days. They show that characteristics of observed meanders do not agree with a theory that the oscillations are excited by inertial oscillations, or a theory representing the tropical cyclone as a rotating cylinder.

Holland and Lander propose that medium-scale (say, deflections on the order of 100 km and times of 1-2 days) meanders may arise from nonlinear interactions with mesoscale convective complexes (MCC). Specific characteristics of an MCC in terms of spatial scales on the enhanced infrared imagery, ellipticity and durations (greater than 12 h) have been defined by Maddox (1980). Holland and Lander show a case of Typhoon Sarah during 1989 that had a long-lasting MCC (which they code named as Alpha) of similar dimensions to Sarah (Fig. 3). The MCC went through periods of active convection, decay and renewed convection. The tracks of the two systems appear to have a mutual cyclonic orbit around a centroid that is analogous to the so-called Fujiwhara effect in binary cyclone interactions (Fig. 4). This centroid, which was assumed to be the midpoint between Sarah and MCC Alpha since the two satellite images had about the same size, tracked steadily toward the west-southwest while the two systems orbited cyclonically.

Holland and Lander numerically simulated the potential effect of MCC Alpha on the track of Sarah by assuming it had the same outer circulation as Sarah. Such a circulation did indeed contribute to a southwestward deflection in Sarah's track (not shown). Without direct observations, it is not possible to verify whether MCC Alpha had an independent mesoscale circulation as assumed by Holland and Lander.

Holland and Lander suggest that the track impact of the same intensity MCC would decrease as the typhoon intensity increases, which would be consistent with the meander statistics they collected. Since the MCC presently is detected only in the satellite enhanced IR imagery without supporting *in situ* observations, it can not be assumed that all MCCs have the same intensity. Holland and Lander speculate that the period and amplitude would decrease as the MCCs form closer to the center, which would be similar to the Willoughby simulations. The key point is that little is known about the structure and other characteristics of MCCs within the tropical cyclone circulation that may cause significant deviations from a steady, smooth track.

c. Monsoon trough shear influences

Les Carr, who recently served as Deputy Director of the Joint Typhoon Warning Center (JTWC) in Guam, has collected a number of examples of significant track deflections when tropical cyclones form with the monsoon trough. For example, tropical cyclone Caitlin during 1991 exhibited a significant departure from its previous track in association with a mesoscale convective system (MCS). The more generic label of MCS is used here because many of these convective systems in the tropics do not satisfy the horizontal spatial specifications, duration or ellipticity requirements of the midlatitude MCCs (Maddox 1980). The MCS formed to the south of Caitlin within a large monsoon trough. The MCS originated within the strongest southwesterly monsoon flow and rotated from a position south of Caitlin to a position east of Caitlin (Fig. 5). At this time, Caitlin and the MCS appeared to couple and both systems tracked northward perpendicular to the line connecting them, which was to the right of the previous track of Caitlin.

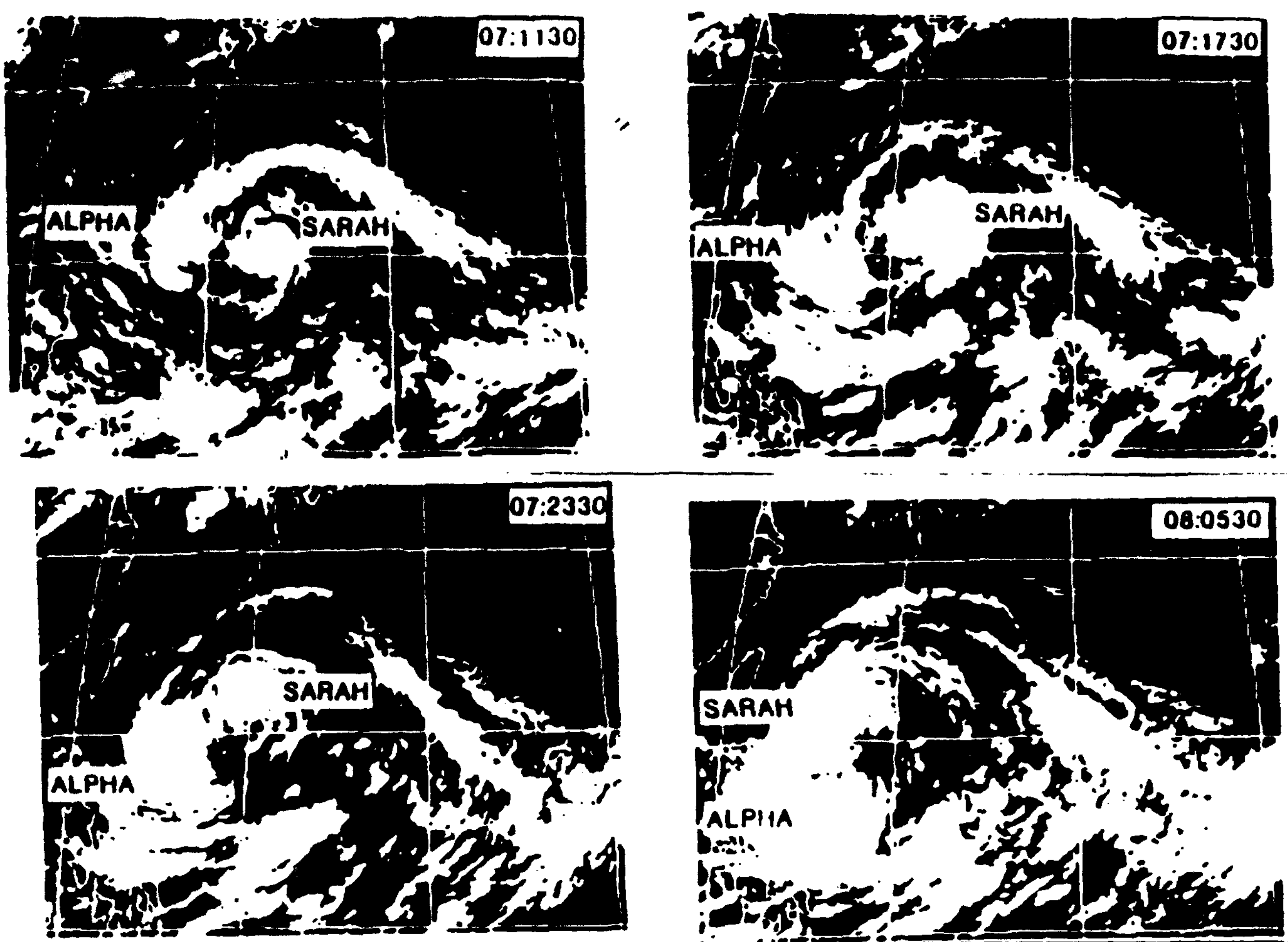

Fig. 3 Geostationary satellite infrared imagery for 7 September 1989 at 1130, 1730 and 2330 UTC and for 0530 UTC 8 September, showing the scales and mutual orbit of MCC Alpha and Typhoon Sarah (Holland and Lander 1991).

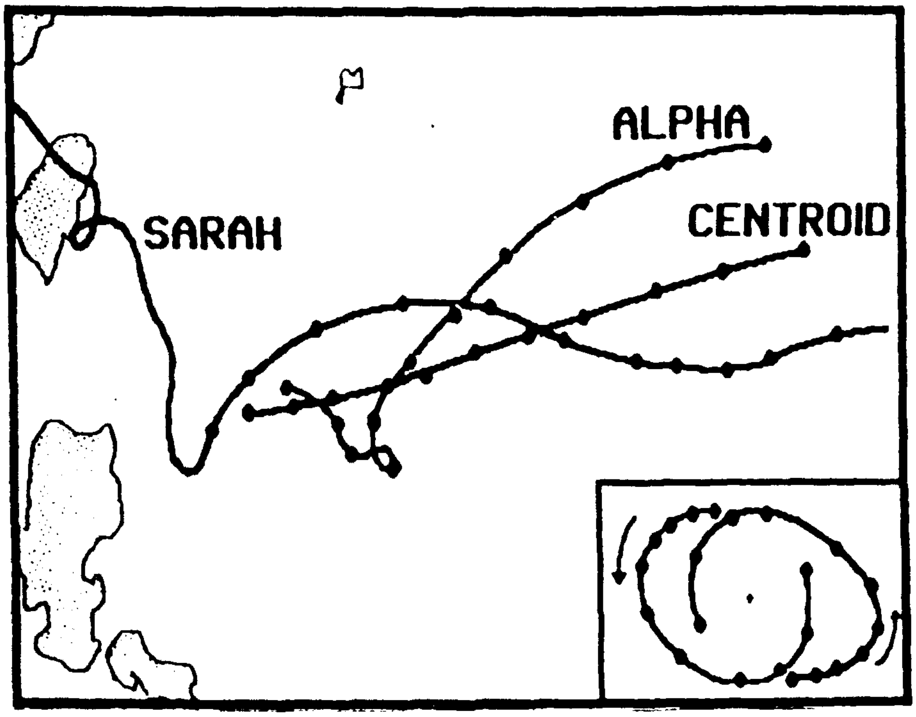

Fig. 4 Positions each 6 h of developing Typhoon Sarah, MCS Alpha and the centroid starting at 23 UTC 5 September 1989. The inset contains the centroid-relative motion of the two systems (Holland and Lander 1991).

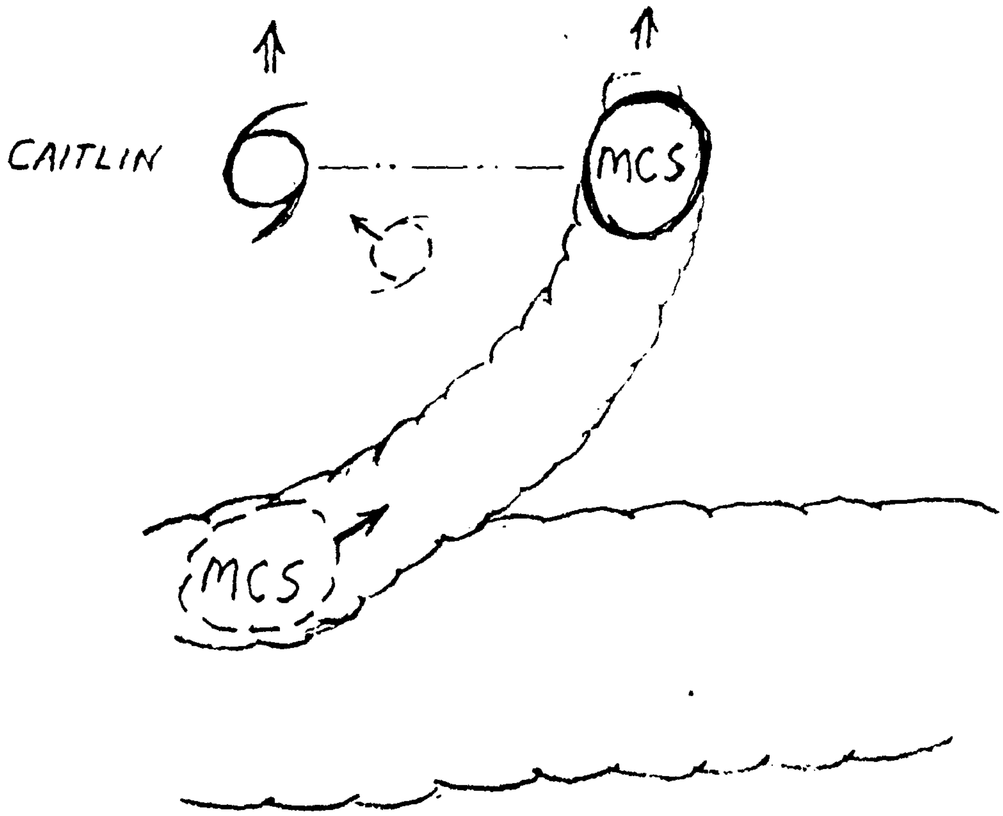

Fig. 5 Schematic of a curved band of the active monsoon trough cloudiness with the positions of tropical storm Caitlin and a MCS at two times. The attached arrows indicate the track directions before (MCS to south of Caitlin) and after (MCS east of Caitlin) the two systems appear to couple along the dot-dashed line.

Two systems at different radial positions from the center of a strongly sheared monsoon trough may appear to have a cyclonic orbit similar to the Fujiwhara effect. One example is the Typhoon Ed and Supertyphoon Flo case during the Tropical Cyclone Motion (TCM-90) field experiment (Elsberry *et al.* 1990). Even though the two cyclones were separated farther than systems expected to have the Fujiwhara effect, Ed and Flo appeared to rotate cyclonically relative to a centroid position for 2-3 days. However, the westward motion of Ed and the northwestward track of Flo could also be interpreted as being due to their positions within a horizontally sheared monsoon trough.

The Holland and Lander case of Sarah and MCC Alpha might also be interpreted to include a sheared monsoon trough influence as well. That is, the motion of MCC Alpha relative to Sarah in Fig. 3 may be due in part to Alpha having been at a greater distance from the center of a monsoon trough in which both systems were embedded. Both the curvature of the long trailing convective band behind Alpha in Fig. 3 and the west-southwestward path of the centroid in Fig. 4 suggest the presence of a large monsoon trough.

The point from these interpretations is a cyclonic rotation about an apparent centroid is not sufficient evidence of an interaction between a tropical cyclone and an adjacent MCS. Since formation of both tropical cyclones and MCSs are favored in a strongly sheared monsoon trough situation, some (or all) of the relative rotation may be due to radial positions within the monsoon trough. This is not to say that a MCS-tropical cyclone interaction may not also be occurring. In the case of Sarah-Alpha, the tropical cyclone Sarah deviated to the left of the expected westward track. In the case of Caitlin, the tropical cyclone apparently deviated to the right of the expected track. Such track deviations are difficult to forecast and contribute significantly to track forecast errors.

Although the presence of an MCS may be detected in the satellite enhanced IR imagery, the structural characteristics of these systems over the tropical oceans are unknown. Understanding the tropical cyclone motion in the presence of an MCS requires *in situ* measurements to provide ground-truth of the structure of the MCS, the structure of the tropical cyclone and the wind structure between the MCS and the tropical cyclone. This is the goal of the proposed mini-field experiment called TCM-92 during July - August 1992.

The following section will describe observations and models of midlatitude MCS that are sustained for some time and are believed to have a structure similar to the tropical MCS to be observed in TCM-92. Consequently, these studies provide structures and evolutions that form the basis for planning aircraft missions during TCM-92 that will distinguish among the hypotheses to be tested (see Section 2).

d. MCS characteristics

(1) **Formation**. Frank and Chen (1991) and Frank (1992) have proposed that the genesis stage of a tropical cyclone may occur in less than one day in association with a MCS. They propose that a mesoscale vortex forms in the stratiform rain region behind a deep convection line due to the organized ascent and latent heat release in the stratiform area (Fig. 6). For certain large-scale conditions, the formation of a large stratiform rain region results in a local reduction of the vertical stability, which reduces the Rossby radius of deformation

$$L_R = Cg\,[(f + \zeta)^{1/2}(f + 2V/R)^{1/2}]^{-1/2}.$$

Because the group velocity Cg is reduced to small values in the moist adiabatic stratiform region, the local Rossby radius may be reduced to about 125 km, which is smaller than the area of the stratiform cloud. In the normal tropical atmosphere, the Rossby radius is much larger than the area of convection, so that the latent heat release is balanced locally by vertical ascent and the energy is radiated from the region via gravity waves. Only small net warming and generation of rotational motion occurs when the Rossby radius is large.

In the special conditions of Fig. 6, the latent heat release is more efficient at increasing the temperatures and rotational winds than a similar amount of heating in a cluster of individual convective clouds in an unsaturated environment. The spinup of the vortex with time, and the descent of the maximum vorticity, in the Frank and Chen model is shown in Fig. 7. Rather than taking days to spinup, the time period is only 12 h, which means the vortex could be developed on the time scale of a diurnal cycle of deep convection. Once the stratiform region becomes well-established (Fig. 6), the vorticity increase is almost entirely due to stretching. That is, the vertical motion associated with the latent heating in the stratiform region is being converted into rotational motion.

The model-generated mid-level cyclonic vorticity and anticyclonic vorticity aloft are shown in Fig. 8. Notice that the horizontal scale is of the order of 100 km at 500 mb and about twice that at 200 mb. Frank and Chen propose that the formation of such a mesoscale vortex may occur in tropical maritime cloud clusters via this process of reduced Rossby radius in the stratiform cloud region. Although the details regarding the necessary and sufficient environmental conditions (and possible role of ice microphysics) are not known, the Frank and Chen model provides a plausible explanation for why a satellite-observed MCS may contain a mesoscale circulation that could interact with a tropical cyclone.

(2) <u>Maintenance</u>. Another key ingredient is the long-term maintenance of the MCS so that the interaction with the tropical cyclone can persist long enough to significantly alter the track. Since the maximum cyclonic vorticity is in the midtroposphere and the anticyclonic vorticity is found aloft (Fig. 8), the thermal structure must be cool in the lower and upper troposphere, with a warm core between the midtroposphere maximum and about 200 mb. A long-standing problem in understanding tropical convection is what maintains the convection within a cool near-surface layer. In the Frank and Chen (1991) model, the convective line remains coupled to the stratiform region (Fig. 6). In combination with the rear inflow jet, the mesoscale ascent is maintained provided adequate (but evidently not too large) values of convective available potential energy (CAPE) are provided to the stratiform region.

Raymond and Jiang (1990) have proposed a theory for long-lived MCSs in the midlatitudes that might also be relevant to TCM-92. Their mechanism involves an interaction between quasi-balanced vertical motions and the diabatic effects of moist convection (Fig. 9). A low-level inflow is hypothesized to provide a continual source of water vapor that ascends over the raised isentropic surfaces associated with the evaporatively cooled down-draft region below the midtropospheric positive potential vorticity anomaly. In the midlatitudes, the cold highs below the MCS are quite intense and the lifting of the warm air at the boundary of the cold high is sufficient to cause condensation. The Raymond and Jiang model produces a cyclonic circulation in the lower troposphere (Fig. 10a) such that air parcels ascend on the east side and descend on the west side. An anticyclonic circulation is created at 10 km (Fig. 10b). The Raymond and Jiang model provides a long-lived, self-contained MCS because the interaction between the convection is with a mesoscale lifting mechanism associated with potential vorticity anomalies of a strength comparable to the ambient potential vorticity.

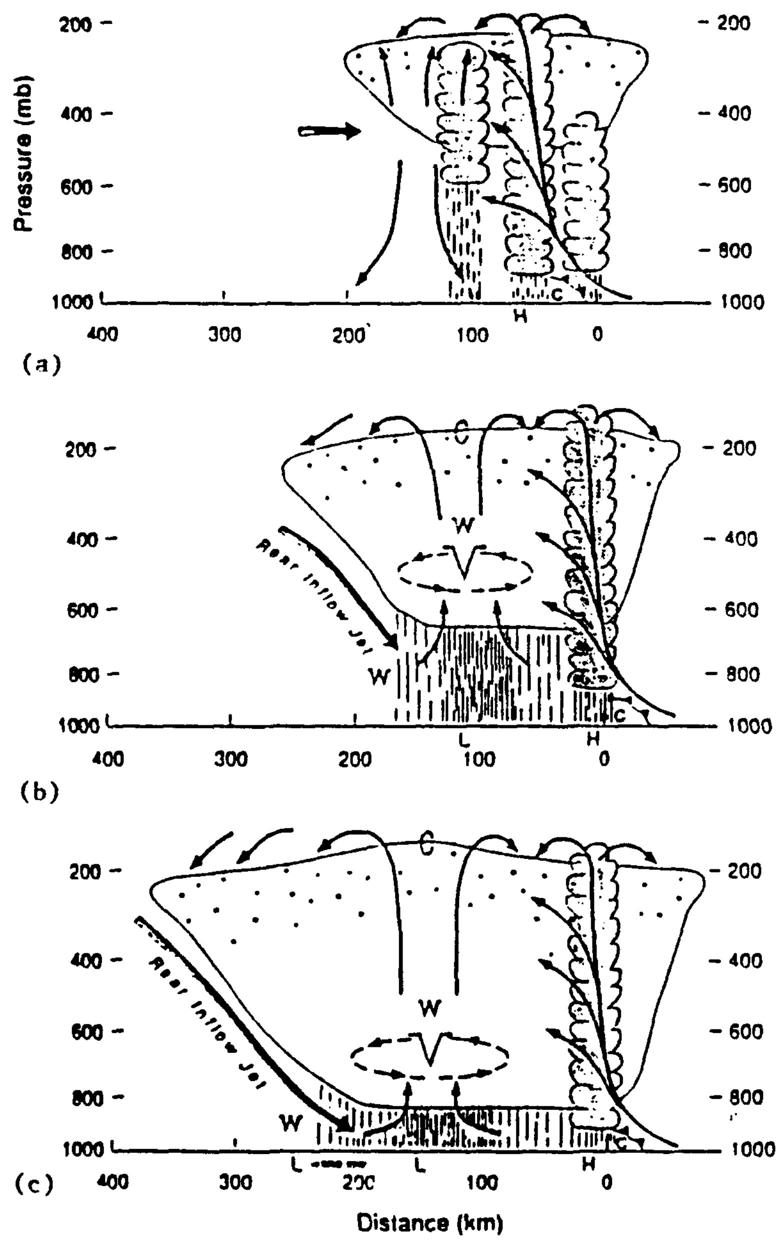

Fig. 6 Schematic diagrams of the structure of an MCC and the associated mesovortex at (a) initial stage, (b) mesovortex genesis stage, and (c) mesovortex intensification stage (Frank and Chen 1991).

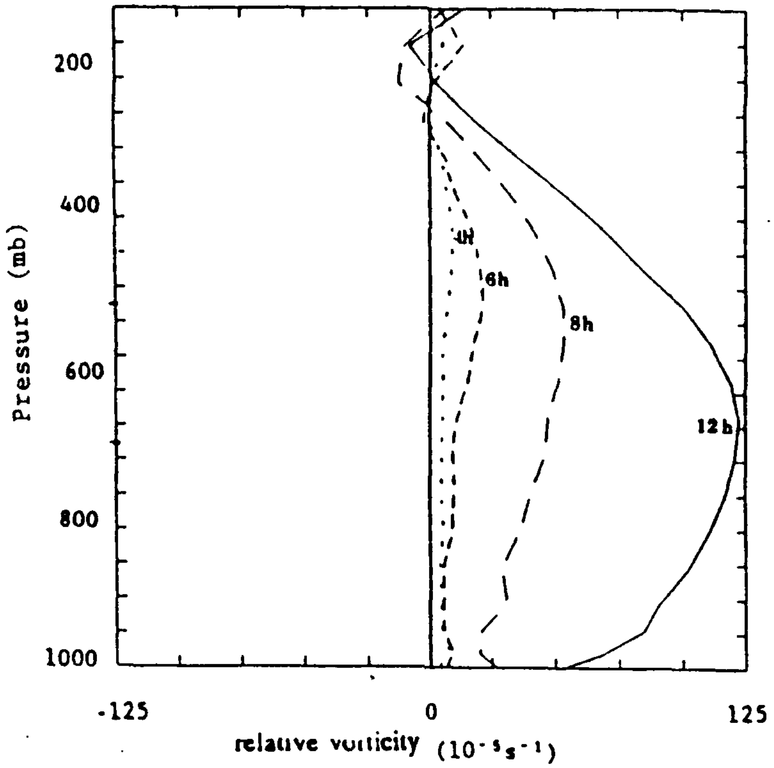

Fig. 7 Downward displacement of the relative vorticity maximum in the stratiform rain region at selected times during the numerical model integration of Frank and Chen (1991).

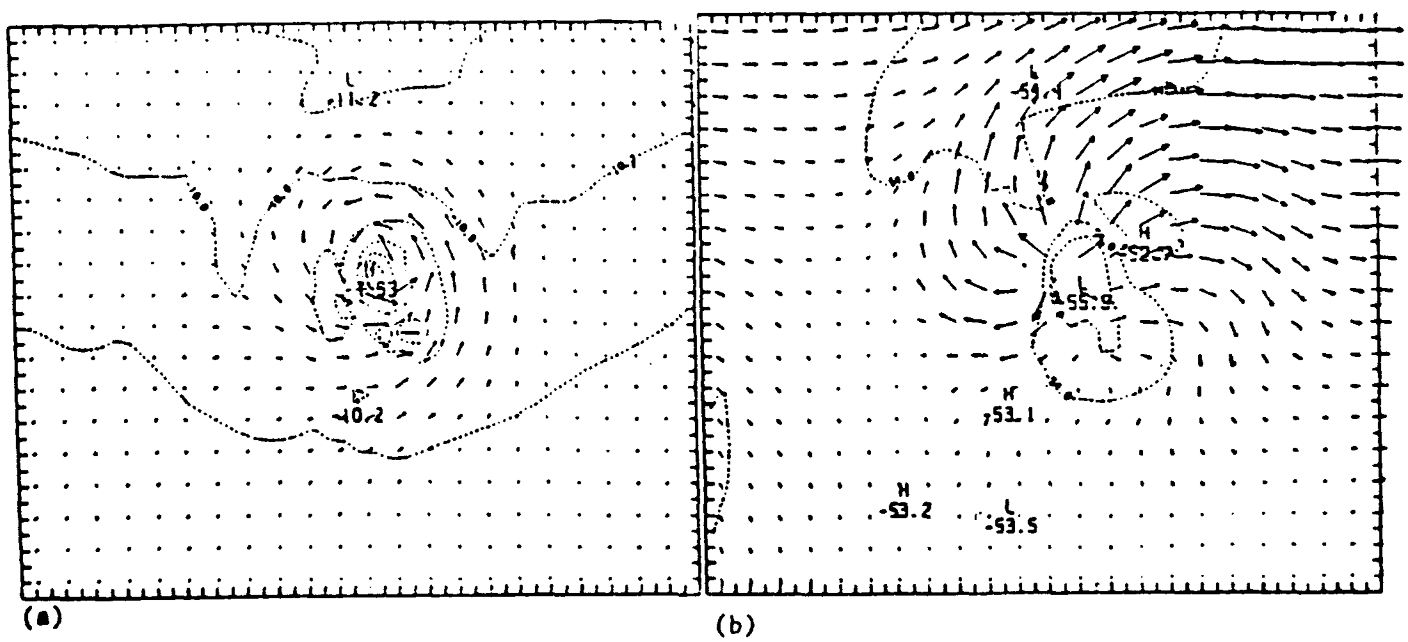

Fig. 8 Relative wind vectors in a coordinate system moving at the speed of the vortex and temperature (°C, dashed lines) at (a) 500 mb and (b) 200 mb. Each grid point is 25 km (Frank and Chen 1991).

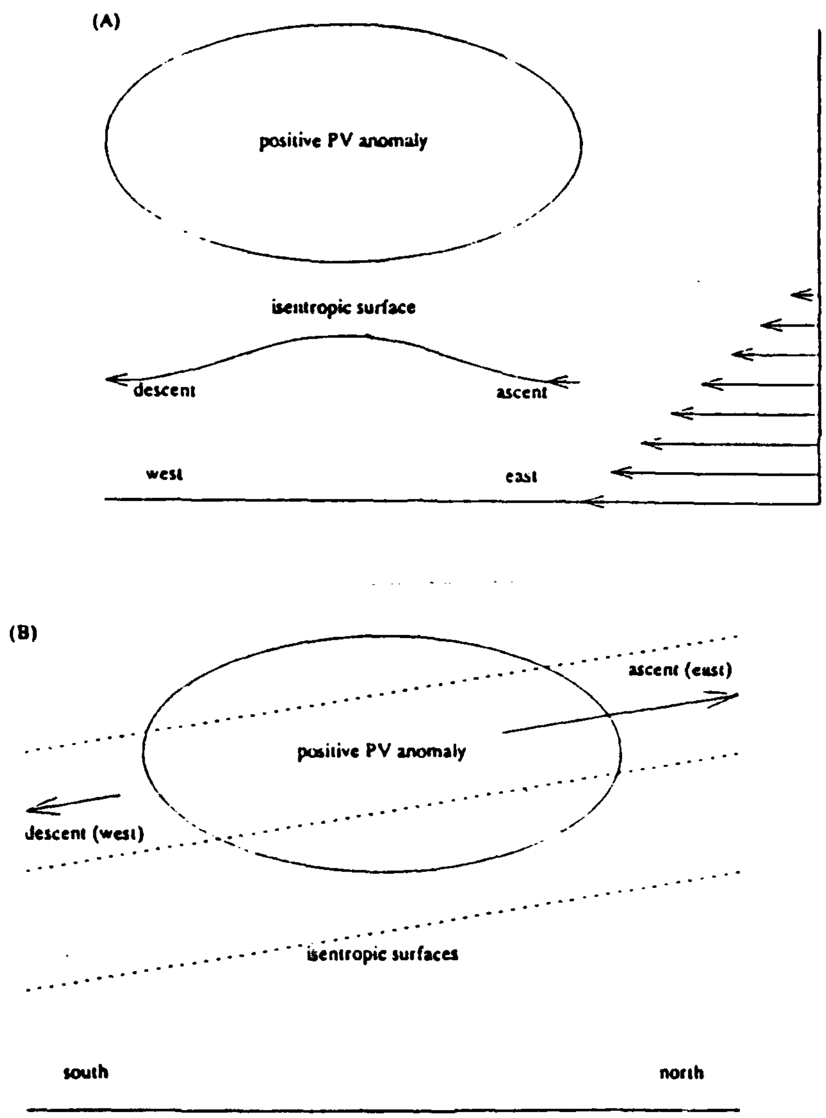

Fig. 9 Sketches of mechanisms by which lifting might occur in the presence of a potential vorticity anomaly in shear that is confined to the east-west plane and is limited to below the potential vorticity anomaly. (a) In a frame in which the anomaly is stationary, the relative environmental wind induces ascent and descent on the perturbation isentropic surface caused by the potential vorticity anomaly. (b) Potential vorticity anomaly viewed from the east with the tilted isentropic surfaces (dashed lines) associated with uniform ambient westerly shear through the depth of the illustration. The cyclonic circulation around the anomaly causes ascent in the northward-moving air on the east side and descent in the southward-moving air on the west side (Raymond and Jiang 1990).

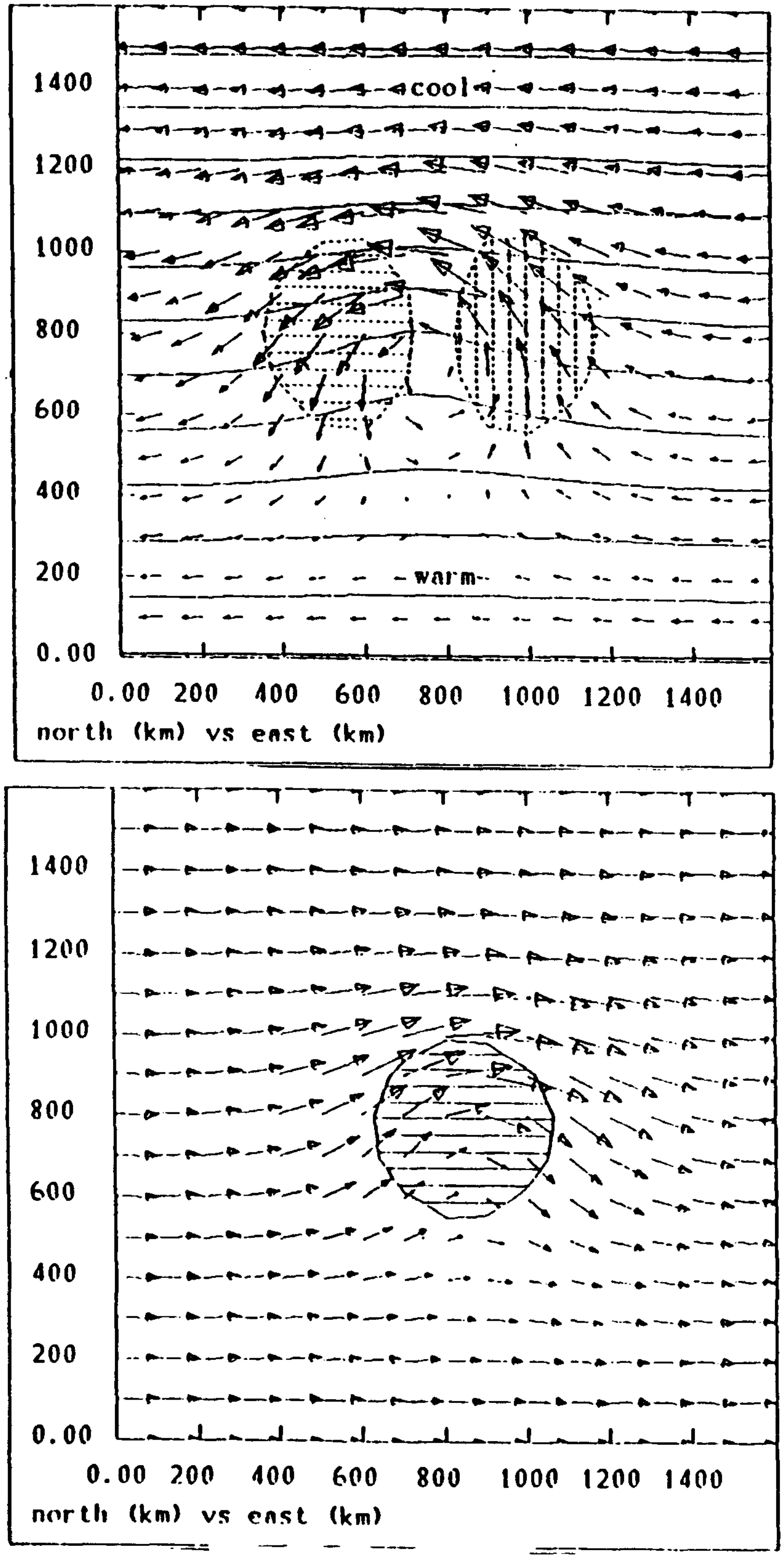

Fig. 10 Flow on horizontal sections at (a) z = 3 km and (b) 10 km after 10^4 s of integration of the Raymond and Jiang (1990) model. Potential temperatures at 1°K intervals and updrafts/downdrafts exceeding 0.5 cm/s are indicated in (a). Region of negative potential vorticity anomalies exceeding 0.33 pvu is hatched in (b). A wind vector of 100 km length corresponds to 3 m/s in (a) and 5 m/s in (b).

Hertenstein and Schubert (1991) have also modelled diagnostically the potential vorticity anomalies in the wake of midlatitude squall lines. Based on observations from the PRE-STORM experiment, they suggest that squall lines with trailing stratiform regions may be associated with large, positive midtropospheric potential vorticity anomalies in their wake. Hertenstein and Schubert force a two-dimensional semi-geostrophic model in isentropic and geostrophic coordinates with an apparent heat source corresponding to the trailing stratiform-type squall line (Fig. 11a). A strong cyclonic potential vorticity maximum is simulated in the midtroposphere with a broad but shallow anticyclonic maximum aloft (Fig. 11b). Notice that the horizontal scale of the anticyclonic vorticity region aloft is about twice that of the cyclonic region. Whereas the wind maxima ($\pm$ 5 m/s) associated with the midtropospheric cyclone are separated by about 250 km, the wind maxima ($\pm$ 9 m/s) associated with anticyclone are about 450 km apart. Lower temperatures below, higher temperatures above, and the midtropospheric vorticity maximum are simulated in the Hertenstein and Schubert model. This diagnostic model suggests that diagnosed midtropospheric vortices in the stratiform region are quasi-balanced wind and mass fields associated with convectively produced potential vorticity anomalies in the midlatitudes.

Fritsch (1992) has proposed a mechanism in which new deep convection may form within the cool region of a MCS, and specifically does not require any frictional convergence. Although his observational study was of a midlatitude MCS, Fritsch proposed this mechanism can create an inertially stable warm-core vortex that can lead to tropical cyclone genesis. Fritsch analyzed the development-decay cycle over three days of a long-lived MCS over land. New convection developed in the interior over the cold pool rather than on the boundary as in the Frank and Chen model or the Raymond and Jiang model. The net MCS intensification during the convectively active phase appeared to be well correlated with the strength of that convection. The potential vorticity cross-sections were similar to the MCS models described above in that the positive maximum was at 550 mb and the negative maximum was at 250 mb, and the positive anomaly was approximately half as wide as the negative anomaly. The positive anomaly increased from 100 km diameter on the first day to 200 km on the second day.

An essential difference in Fritsch's observational study relative to the Raymond and Jiang model is that the air trajectories originated upstream of the MCS rather than on the leading edge (Fig. 12). The MCS, which was translating with midtropospheric winds, moved slower than the air in the low-level jet that was providing the continual moisture source. However, the lifting mechanism is still the isentropic ascent over the evaporatively cooled downdraft air as in the Raymond and Jiang model (Fig. 9).

(3) <u>Application to tropical MCS</u>. As indicated above, few observations exist to describe the structure and evolution of MCSs in the tropics. Indeed, this is a primary motivation for the TCM-92 mini-field experiment during July - August 1992.

The basic physical mechanisms for formation of a mesoscale vortex within the stratiform rain area would appear to operate as well in the tropics as in the midlatitudes. The requirement for a vertical wind profile that has higher velocities at low levels than in the midtroposphere (Figs. 9 and 12) would be satisfied in the monsoon trough region (Fig. 13). Strong southwesterly winds often are found at low levels on the equatorward side. Although strong tradewind flows often are found on the poleward side as well, some limited (personal observation) experience suggests that the MCSs are more prevalent on the equatorward side. The lower inertial stability, and the higher equivalent potential temperatures, of the air approaching from the equatorward side would tend to favor MCSs in that branch. Multiple MCSs are common in this equatorward branch and a common forecast problem is to decide which of these MCSs might intensify into a tropical

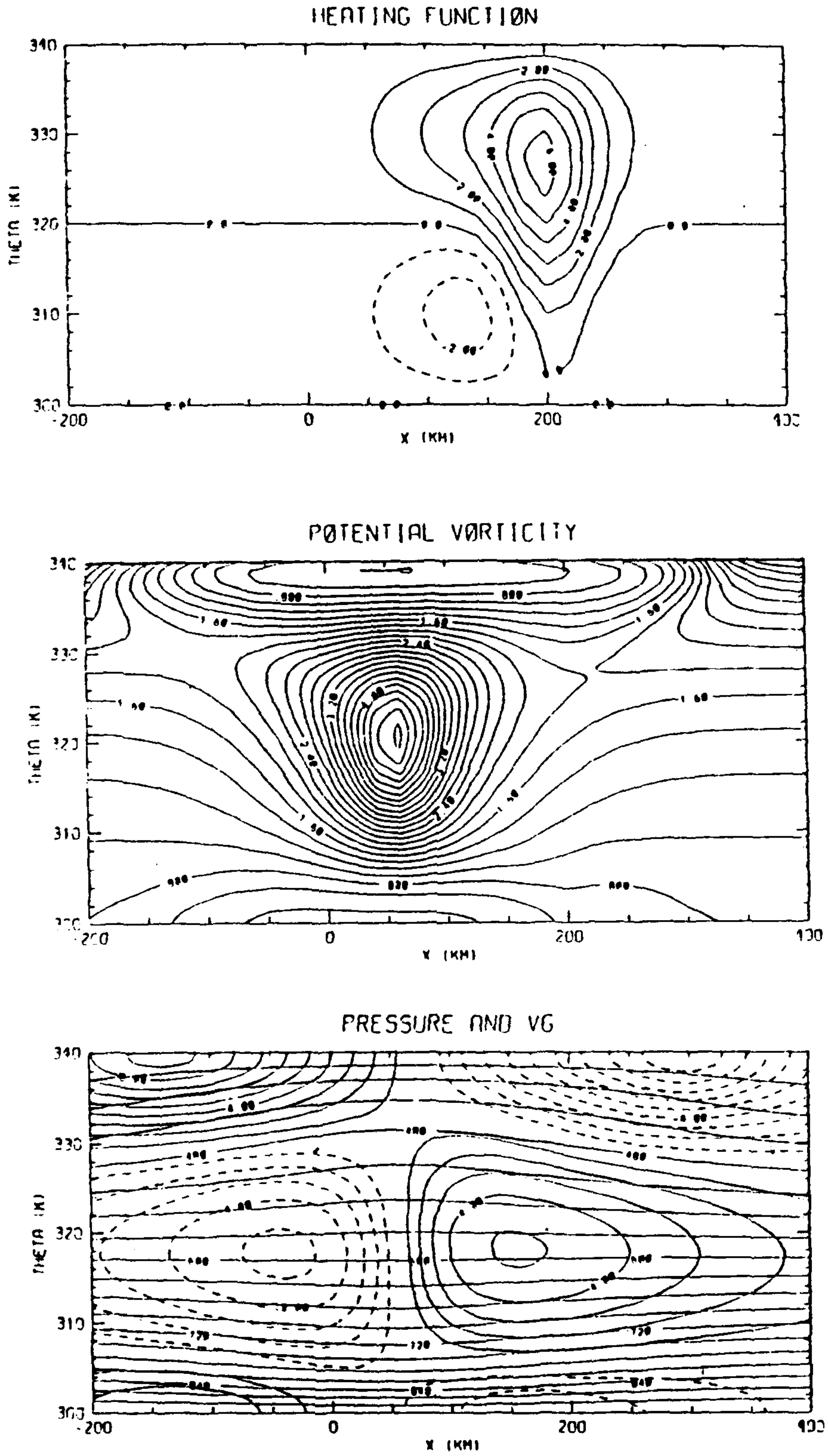

Fig. 11 Potential vorticity (middle), wind speeds and isotherms (lower) diagnosed in the Hertenstein and Schubert (1991) model with the heating function (top) that corresponds to a squall line with a trailing stratiform rain region. Heating is indicated by solid contours while dashed lines represent cooling. Note that the contour interval for the potential vorticity field is 0.2.

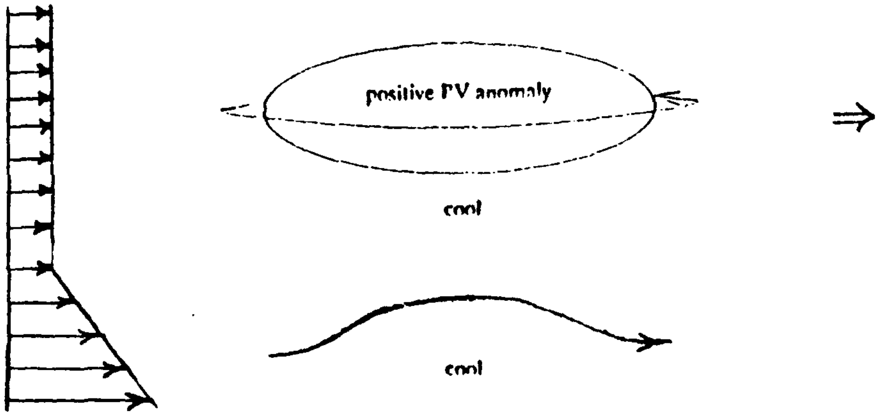

Fig. 12 Schematic of the sheared environmental wind profile and low-level trajectories of air parcels in a rear-inflow case deduced in an observational study by Fritsch (1992).

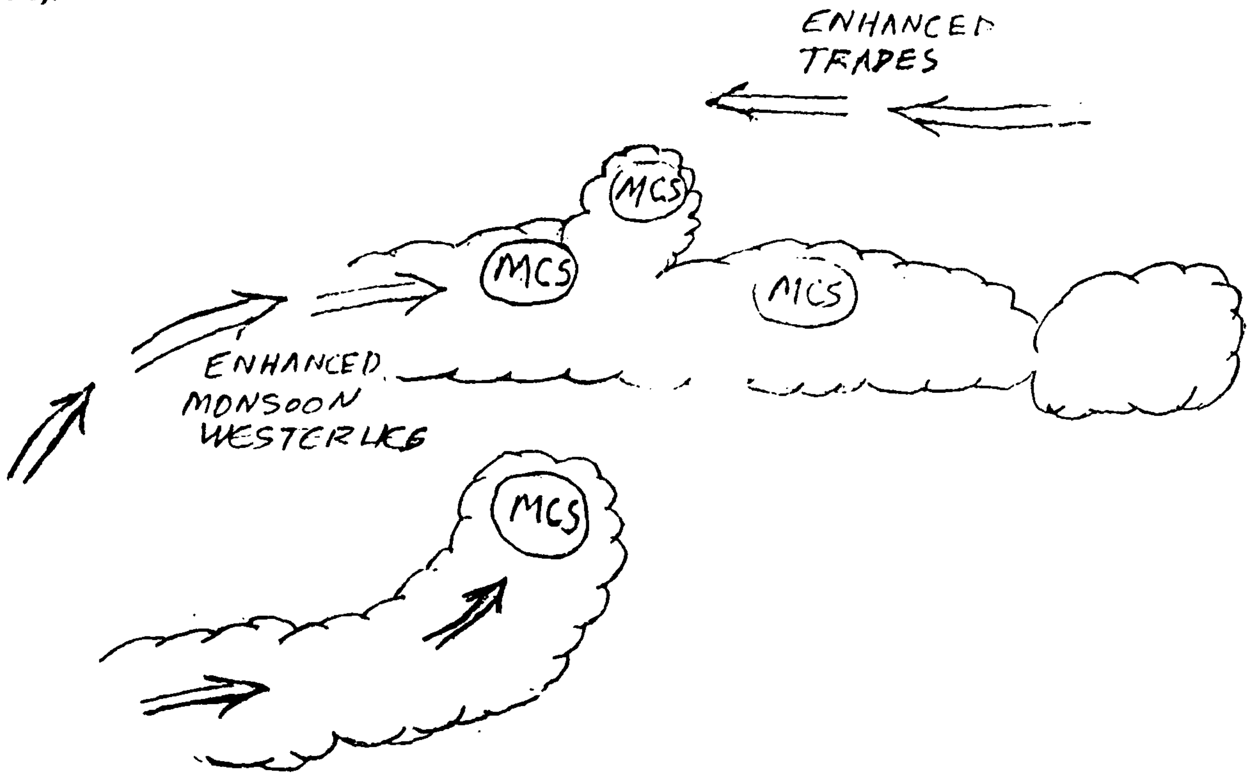

Fig. 13 Schematic of early stage (top) and later stage (bottom) of multiple MCSs in an active monsoon trough region between enhanced monsoon westerlies and enhanced trade wind easterlies. In the later stage, development and/or translation of a MCS northward has resulted in a fishhook shape to the monsoon trough convection with sustained low-level flow into the rear of the MCS as in Fig. 12.

depression. Again based on limited personal observations, the poleward MCS tends to be favored, perhaps because of the larger Coriolis parameter being more favorable to induce rotational motion for the same low-level convergence. Mark Lander of the University of Guam is developing a climatology of MCS occurrences that will provide a more quantitative basis for discussion of the spatial distribution and intensification characteristics.

When the poleward MCS develops into a tropical cyclone, or any MCS within the equatorward branch develops a significant organization and moves poleward, the convective band may be curved cyclonically into a "fishhook" shape (Fig. 13). Continuation of this trend can lead to the convective band extending cyclonically around the poleward branch of the monsoon trough as in Fig. 3. The key concept related to the MCS models is that a low-level speed maximum is likely to be sustained over a period of days. Thus, the continual moisture flux into the rear of the MCS as in the Fritsch conceptual model (Fig. 12) would seem to be possible. Consequently, conditions for the MCS to be sustained during each diurnal minimum in convection, and for MCS rejuvenation and growth during the subsequent diurnal maximum in convection, would seem to exist in the monsoon trough. As indicated previously, such long-lived MCSs are required for significant deflections of the adjacent tropical cyclone.

One different aspect of the tropical maritime MCS versus the observations and models of the MCS over land in the midlatitudes is the likely magnitude of the isentropic lifting at low levels. In the midlatitudes, the rain-induced cooling below the high cloud bases can lead to strong downdrafts. Over land, this cold air may be little modified by surface fluxes, and strong cold highs may persist. In the tropics, the cloud bases of the convective clouds are lower and the low-level rain cooling is smaller. However, saturated mesoscale downdrafts adjacent to the convective clouds do reach the ground and spread forward to form the lifting mechanism in tropical squall lines. The mesoscale downdrafts below the trailing stratiform rain region probably have too little rain-cooling to create substantial cold pools with significant isentropic slopes as in the midlatitudes (Fig. 9). However, the high θ_E values of tropical air do not require as much vertical lifting to trigger convection. Consequently, the feasibility of the Fritsch rear-inflow mechanism for sustaining ascent and latent heat release in the stratiform rain region must be demonstrated from observations of tropical MCSs. The alternative may be an internal mechanism (perhaps related to the ice microphysics) that sustains the mesoscale updraft within the stratiform rain region, and thus the possibility for continued intensification of the midtropospheric vortex.

At least in the early stages of the MCS, little reflection of such a midtropospheric vortex can be found in the surface winds or pressures. Thus, frictional Conditional Instability of the Second Kind (CISK) does not play an essential role during the early stages. Tapping into the surface oceanic energy source locally requires a downward extension of the vortex and high winds into the surface layer. Frank and Chen (1991) note that they are searching for the conditions under which the MCS circulation is extended downward since the frictional CISK plus the local oceanic heat source would provide two additional mechanisms for intensification to the tropical depression or tropical storm stage. Although TCM-92 is intended to provide observations necessary to understand tropical cyclone motion, these observations will be of interest to understand genesis as well. Thus, additional flight plans for TCM-92 will be designed to understand the structure of MCSs when a tropical cyclone-MCS situation has not developed yet.

2. Hypotheses

Given the scientific background in the first chapter, tentative hypotheses have been formulated as a basis for planning typical flight patterns for the WC-130. These hypotheses are presented below in the order of priority for TCM-92 to understand the tropical cyclone motion problem. Thus, the highest priority will be given to the first three hypotheses that require observations of the structure of a MCS embedded in a tropical cyclone, the corresponding structure in the tropical cyclone, and the intervening interaction zone between the two systems. Flight tracks 1 and 2 in the Appendix are designed to obtain the required observations in the MCS-tropical cyclone interaction situations.

An active monsoon trough (Fig. 13) typically has a number of MCSs prior to the formation of the first tropical cyclone event during the active phase (in most cases one of the MCSs becomes the tropical cyclone). Thus, almost an equally high priority is given to obtaining measurements of the three-dimensional structure of an isolated MCS in more detail than can be accomplished with a single-aircraft when both the MCS and the tropical cyclone must be observed. Flight track 3 in the Appendix is an example of such a mission. These detailed structure observations also are necessary for specifying the initial conditions in 3-d numerical models of the MCS-tropical cyclone interaction. If enough cases are obtained, these observations are expected to provide an empirical model of the MCS structure in relation to the satellite enhanced-IR signature characteristics for both JTWC use and for insertion in dynamical track prediction models.

The third priority is a multiple MCS mission that would be exercised if two MCSs are close enough to be interacting. As these measurements would test a tropical cyclone genesis hypothesis involving interacting MCSs, they are of considerable scientific interest, but must be regarded as third priority in TCM-92. The flight tracks would be similar to those for the interacting MCS-tropical cyclone tracks 1 and 2 in the Appendix.

Hypothesis 1. Long-lived tropical Mesoscale Convective Systems (MCS) have a three-dimensional wind and thermal structure similar to a midtropospheric vortex in the stratiform rain region of a midlatitude MCS, and have sufficient horizontal extent to cause a mutual interaction with a tropical storm or weak typhoon via a Fujiwhara-type effect that results in track deviations of 100 km over a day.

Hypothesis 2. Long-lived tropical MCSs that maintain a quasi-stationary position relative to an associated tropical cyclone cause approximately 100 km deflections in the cyclone track via the divergent circulation and its interaction with the symmetric vorticity field to create an asymmetric wavenumber one circulation.

Hypothesis 3. Relative cyclone track displacements of a MCS and a tropical cyclone can be related to their radial positions within the horizontal wind shear field of an active monsoon trough.

Hypothesis 4. Tropical cyclone genesis is caused by the merger of two or more interacting Mesoscale Convective Systems to create a system with greater vorticity.

As implied above, the expected scenario involves the beginning phase of an active monsoon trough. As the large-scale circulation patterns (Fig. 13) become more favorable, MCSs are expected to be formed. Some of these MCSs will satisfy the (mostly unknown) environmental conditions to rapidly (within 12 h) develop a midtropospheric vortex. The

first mission should begin (if possible) at this time and will be a MCS structure mission since a tropical cyclone will not have developed yet. If no tropical cyclone has developed yet, the second mission should follow in 26 h (cycle time for aircraft missions that last 11 h) into the same MCS if possible. If not, the strongest MCS within aircraft range should be selected. If the appropriate situation develops with interacting MCSs (Hypothesis 4), the third priority mission might be attempted. On the third day, it is likely a tropical cyclone will have developed, and the first priority mission should be flown. Other alternatives can be considered if no tropical cyclone has developed. Detailed schedules for the missions over a period of three days are presented in Section 4.1.

Many variations upon the basic scenario must be considered. For example, the monsoon trough may already be active when the WC-130 arrives in Guam, and a tropical cyclone may already be in existence. Flexibility is essential in planning the missions, and in adjusting to changes in conditions while the aircraft is in flight. A key factor is the distance of the MCS-tropical cyclone system from Guam. Thus, the flight tracks in the Appendix are only for planning purposes and will be adjusted as the situation requires.

3. Aircraft Operations

a. Mission

The primary mission of the Tropical Cyclone Motion (TCM-92) WC-130 aircraft will be to provide three-dimensional measurements (flight-level plus dropwindsondes) of the internal structure and the interaction zone between tropical cyclones and adjacent Mesoscale Convective Systems (MCS's) that cause significant track deflections in western North Pacific tropical cyclones. Documentation of the structure and structure changes in the tropical cyclone and the adjacent MCS make the aircraft dropwindsondes an essential component. Penetrations of the tropical cyclone center, as well as the center of the MCS, will be necessary. Because of the differential motions between the tropical cyclone and the MCS, the interaction event may occur at an uncertain time and in a location not necessarily well-resolved by the normally sparse western North Pacific rawinsonde network. Consequently, the detailed observations from the aircraft will be required to augment the rawinsonde data in the region of the expected interaction zone to meet experiment objectives described in section 1. The ultimate goal of the experiment is to coordinate flight paths with satellite imagery in order to develop empirical relationships to benefit forecasters at the Joint Typhoon Warning Center (JTWC), Guam.

Highly accurate fix information will be necessary if track changes due to tropical cyclone-MCS interaction are to be documented. The WC-130 aircraft will provide high accuracy fixes of both the tropical cyclone and the MCS. The tropical cyclone center will be fixed using wind, temperature, pressure and radar information evaluated subjectively by the Aerial Reconnaissance Weather Officer (ARWO). Center positions will be particularly important when an eye (or closed circulation) is not clearly defined in the satellite imagery. Although the general location of the MCS is revealed by the satellite imagery, the aircraft observations are required to detect the structure and center location.

b. Aircraft capabilities

One Air Force WC-130 will be available to fly data-gathering missions from 21 July-18 August). This four-engine turboprop aircraft has the Improved Weather Reconnaissance System (IWRS) that incorporates inertial navigation equipment, automatic data acquisition and satellite communications. An IWRS receiver will be installed at JTWC to obtain the data in real-time and transmit updated satellite information to the aircraft crew. In a typical 10 - 12 hour mission, the WC-130 aircraft can fly 2500 - 3000 n mi to include a portion of the mission at 300 mb.

An essential capability of the aircraft is the Omega DropWindsonde (ODW). The desirability of maximum ODW release elevations (i.e., depths of ODW sounding) will be balanced against the requirements for horizontal spacing (as small as 100 km may be desirable) of the soundings because of the slow fall rate (1,000 ft/min) and the restriction of having only two sondes in the air at any time.

Permission to operate in the near-vicinity of thunderstorms is essential since both the tropical cyclones and the MCS will contain deep convective clouds. Deviations from the flight tracks as necessary to avoid hazardous conditions and assure crew and aircraft safety is assumed.

c. Aircraft personnel

The aircraft will have a TCM-92 Chief Aircraft Scientist and possibly other TCM-92 observers to document weather events on each mission. The TCM-92 Chief Aircraft Scientist will be responsible for scientific crew members, and will coordinate with the other members of the TCM-92 forecast team at JTWC who will be monitoring the synoptic situation via satellite imagery. The TCM-92 Chief Aircraft Scientist will represent TCM-92 interests if decisions about flight track modifications or other scientific aspects of the assigned mission must be made inflight. This coordination will be with the ARWO on the WC-130. The aircraft Commander (Pilot) has final authority over operation of the aircraft and safety of flight.

The USAFR WC-130 aircrew will be seven persons, which includes the ARWO and two dropwindsonde system operators (DSO). These personnel provide near-real-time flight-level observations in the RECCO code, one-minute flight-level observations, vertical observations in the TEMP DROP code at the desired locations along the flight track, and detailed vortex messages. The satellite communication capability allows transmission of RECCO, vortex data reports, and ODW reports to a portable ground satellite communication station to be located at the Experimental Operations Center (EOC) at JTWC. The one-minute reports (MINOBs) will be transmitted at 20 minute intervals. More complete flight-level data will be recorded and provided on floppy disks at the end of the mission.

An HF-voice communication link between the Experiment Operations Center and the aircraft via a phone link through the USAF monitoring stations at Andersen Air Force Base or Kadena Air Base will be arranged as a backup communications source.

d. Dropwindsonde operations

The U. S. Air Force Reserve has provided an adequate supply of Omega dropwindsondes (ODW) for use on the WC-130 during TCM-92. One important advantage of the ODW is that it can be used throughout the Northern Hemisphere. For example, the Hurricane Research Division of NOAA has successfully used the ODW in their Synoptic-Flow Experiments in Atlantic and eastern Pacific storms. Unfortunately, the weight of the ODW precludes its use over inhabited areas. Clearance for ODW soundings over the ocean must be requested to assure that no aircraft at lower levels is endangered. These soundings typically yield winds averaged over three minutes, which is necessary to minimize errors in the calculations of winds from the Omega navigation system. Due to the three-minute averaging, wind calculations are not possible near the ground. The first wind report from the ODW will be about 2000 ft below flight level.

As indicated above, the slow fall speed (1000 ft/min) of the ODW means that the sonde will be transmitting for longer times as the WC-130 achieves higher flight altitudes. Since only two sondes can be transmitting simultaneously, the aircraft will travel a greater horizontal distance before another sonde can be launched. Thus, a trade-off between maximum flight altitudes and a desire to have minimum horizontal distances between sondes is required. During center penetrations, and in the interaction regions between the tropical cyclone and the MCS, horizontal resolution of 100 km, or less, is desirable. Outside of these regions, an increase in horizontal spacing is acceptable. It is anticipated that approximately 20 sondes will be launched each mission.

If a sonde fails (about 10 - 15% of the time), the ARWO and the TCM-92 Chief Aircraft Scientist should confer as to whether the aircraft should delay in that area to achieve a successful launch. In general, a single failure within a long leg of successful observations will not justify a special effort to acquire a sounding. A sequence of failed sondes will require a delay. Observations at the end of a leg in the MCS are very important, and a second launch should be attempted.

Quality control procedures have been developed for the ODW. These procedures must be executed carefully to assure high-quality observations for real-time and archived data sets.

e. Aircraft basing

The WC-130 will operate from Andersen Air Force Base on the island of Guam. If Guam should be threatened by a typhoon, the aircraft could be evacuated to Kadena Air Base on the island of Okinawa or Yokota Air Base near Tokyo, Japan. If flights east of Guam are required, an emergency recovery location may be Kwajalein Island.

f. Aircraft mission planning

General responsibility for the employment of the WC-130 aircraft resides with the Experiment Operations Director, who will determine mission assignments in conjunction with the Experiment Operations Team and the TCM-92 Chief Aircraft Scientist.

The Experiment Operations Center/Aircraft schedules that would be followed during periods of potential aircraft research missions are described in Section 4. Missions have been arranged so that the aircraft would be near the center of the MCS at one of the synoptic times (0000, 0600, 1200, 1800 UTC). These times are selected to correspond with the diurnal maxima (1800 UTC) and minima (0600 UTC) periods for convective activity, or with periods of supporting environmental data (maximum at 00 UTC and somewhat reduced at 12 UTC). The alert times are based on the requirement for 12 hours crew rest and three hours of flight preparations prior to take-off.

g. Flight tracks

Samples of flight tracks (Appendix) have been prepared by CAPT Eric McKinley (USAF) of the Naval Postgraduate School. For safety considerations, the WC-130 aircraft may not be able to fly near the freezing level. Unfortunately, this would be near the optimum level to map out the midtropospheric vorticity center with flight-level winds (see Figs. 6 and 7). If the first penetration of the MCS is at 10,000 ft, to stay 5,000 ft below the freezing level, a second penetration at high levels is required.

Three Air Traffic Control (ATC) centers (Tokyo, Guam and Oakland) may be involved in various portions of the experimental domain. The Tokyo ATC will be presented sample flight tracks for pre-approval prior to the experiment. Hopefully, some small deviations from a fixed point-time plan will be acceptable because our plans are oriented relative to the typhoon position, which would otherwise have to be known very accurately 24 - 30 h in advance. More flexibility may be permitted for the WC-130 which will generally be flying below the commercial flight levels most of the time.

h. Duties of TCM-92 aircraft personnel

The TCM-92 Aircraft Chief Scientist will be the only TCM-92 experiment team member to routinely fly with the WC-130 crew on every mission. Requests for additional TCM-92 members, other scientific observers, news media personnel or dignitaries to fly with the WC-130 must be cleared with the USAFR Reconnaissance Task Force Commander (RTFC). These summaries are patterned after the 1990 Hurricane Field Program of the Hurricane Research Division (HRD).

TCM-92 Aircraft Coordinator:

1) Responsible to the Experiment Operations Director for the implementation of the aircraft operations plan.

2) Leads discussion of aircraft missions in the Experiment Operations Team meetings, and develops preliminary flight tracks in conjunction with the Aircraft Chief Scientist and Experiment Operations Director following the meeting.

3) Coordinates final flight track request with the Aircraft Chief Scientist to be presented to AWRO and Navigator, and is responsible for communications between the EOC and Chief Aircraft Scientist during flight missions.

4) Maintains an inventory of flight hours, expendables for aircraft missions and other factors that relate to the availability of aircraft assets.

TCM-92 Aircraft Chief Scientist:

1) Has overall **scientific** responsibility for achieving the mission objectives.

2) Participates is Experiment Operations Team meetings and works with Aircraft Coordinator and Experiment Operations Director to develop preliminary flight track plan following the meeting.

3) Finalizes flight track request in conjunction with Aircraft Coordinator and discusses with ARWO and Navigator prior to filing of flight track

4) Makes in-flight decisions concerning alterations of (a) specific flight patterns; (b) instrumentation operation; and (c) assignment of duties to onboard TCM-92 scientific personnel.

5) Acts as project supervisor on the aircraft and is the focal point for all interaction of TCM-92 personnel with the operations or visiting personnel.

6) Serves as a liaison between the RTFC and the Experiment Operations Director.

7) Serves as the TCM-92 representative at all preflight and postflight crew briefings.

4. Experiment Operations Center

a. Schedule of operations

The primary decision to be made at the Experiment Operations Center (EOC) is the calling of an Aircraft Observing Period (AOP). As indicated in Section 3, the WC-130 crew must go into crew rest about 15 h prior to takeoff. Since the midpoint of each mission (which is when the WC-130 should be within the MCS at either 0000, 0600, 1200 or 1800 UTC) will be about 5 h after takeoff, the crew rest must begin 20 h in advance. Detailed schedules for an AOP at each of the four mission times are given in Tables 1-4.

Notice that the EOC team must begin deliberations about 22 h prior to the midpoint of the mission. A great challenge confronts the TCM-92 Chief Forecaster Mark Lander to forecast the existence and likely track of a MCS given the data sparsity in the tropics and a basic lack of understanding (see Section 1). As indicated at the end of Section 2, different scenarios must be anticipated. Given the uncertainties involved in the forecast process, a final Go decision will be made at 2.5 h prior to takeoff. The EOC team will evaluate the evolution of the meteorological system during the past 12 h compared to the forecast. The desired flight track will then be passed to the WC-130 Navigator, who will evaluate the feasibility of the planned mission and obtain the necessary Air Traffic Control (ATC) clearances.

Once this Go decision is made, the mission will proceed. However, the MCS and/or the tropical cyclone evolution and tracks must be monitored during the pre-flight preparations, the ferry to the region of interest and throughout the scientific measurement program. Fortunately, the satellite communications capability of the WC-130 permits continually monitoring of the flight-level and dropwindsondes in real-time, and direct communications from the EOC to the WC-130 for updating the missions.

The real-time monitoring and track updating requirement sets the activities of the EOC team. Satellite imagery (geostationary and polar-orbiting) must be monitored continually. Both conventional and WC-130 flight-level observations must be plotted and analyzed in relation to the satellite imagery and the planned flight mission. This activity must continue until the WC-130 has completed the scientific portion of the mission and has begun the ferry back to Guam. However, the mission planning cycle must then begin in anticipation of a mission on the following day. If so, the WC-130 personnel will go into a crew rest period immediately after landing. With a 11-h mission, the cycle time is 26 h so that operations on the second (third) day would lag the first day operations by 2 (4) hours. Of course, if the tropical cyclone and/or MCS are closer to Guam, the mission length will be shortened due to reduced ferry times.

The 0000 UTC mission (Table 1) would take advantage of the maximum conventional data in the environment of the tropical cyclone and MCS. This time is near the beginning of the diurnal convection minimum, so that the midtropospheric vortex should be reaching maximum amplitude and horizontal extent (see Figs. 6 and 7). However, this scenario will be difficult to forecast 22-24 h in advance. The early morning take-off time and supporting EOC operations will be somewhat disruptive in terms of human factors.

Although a 1200 UTC mission (Table 3) would have supporting conventional data, it would not be as good as at 0000 UTC. This mission would be early in the diurnal convection cycle, and the midtropospheric vortex should be beginning to intensify at this time. Forecasting the location of the MCS during this phase will be quite difficult. The

late afternoon take-off and early morning recovery are rather undesirable from human factor considerations.

An 1800 UTC (Table 4) also will not have supporting conventional data. This mission would be centered on the diurnal maximum in convection and the midtropospheric vortex should be amplifying most rapidly at this time. Real-time monitoring of the growth of the convection since the early evening (during pre-flight and ferrying periods) would probably allow effective modifications of the flight plans to ensure that the MCS was located and measured well. However, this mission is probably the most taxing of the four missions from a human factors viewpoint.

b. Duties and Procedures during Aircraft Observing Periods (AOP)

The following workstations at the EOC will be manned during each AOP, both to facilitate the expeditious collection of aircraft, satellite and synoptic data associated with the aircraft missions, and to quickly provide the aircrew with recommended flight track changes based on updated information. Each workstation will be supervised by a Workstation Manager and one or more assistants (as necessary).

(1) **Satellite Imagery Workstation.** The Satellite Imagery Manager will be responsible for monitoring and organizing the real-time satellite imagery as it becomes available during the AOP. He/she will work closely with the DET 1 Duty Satellite Analyst to ensure that satellite imagery is made available to the EOC as soon as possible. The present plan is to utilize the NSDS-G receiver to obtain copies of the hourly geostationary imagery for the real-time monitoring function. The DET 1 satellite analyst primarily uses a new display system that allows fixing of tropical cyclones from soft copies only. A high-resolution color printer is attached to this system. Selected (perhaps 3 h during AOP) color prints may be requested if this does not interfere with the DET 1 operational functions.

If possible, a film copy of the high-resolution DMSP or NOAA AVHRR imagery will be obtained for a pass near the WC-130 take-off time. To correlate the dropwindsonde data with the cloud features, acetates will be overlaid on this visual/IR imagery so that the dropwindsonde and flight-level winds and temperatures can be plotted. For example, selected flight-level data and the 400 mb, 500 mb, 700 mb, 850 mb and (near) surface data from dropwindsondes may be plotted on separate acetates as time allows. These plots will provide a basis for recommendations to the EOC Director for flight track alterations.

The second function of the Satellite Imagery Manager will be to obtain digital values of the satellite imagery for use in post-experiment analysis. Detailed analysis of the WC-130 data will require high-resolution imagery for comparison and interpretation. Access to the raw digital values would also allow development and testing of new imagery enhancements to highlight key features revealed in the flight-level and dropwindsonde profiles. Plans for archiving the digital records on tape are being made in conjunction with JTWC personnel to assure that TCM-92 requirements do not interfere with normal operations.

The manager will ensure that all satellite data under his/her control have been transferred to the TCM-92 Data Manager at the end of each AOP.

(2) **IWRS Groundstation Workstation.** The IWRS Groundstation Manager will be responsible for maintaining communications with the WC-130 aircraft. The manager will pass updated satellite information and track change recommendations to the Aerial Reconnaissance Weather Officer (ARWO). If necessary, the manager will initiate phone patches between the EOC and the aircrew through Andersen (or Kadena) Airways.

Incoming reports from the WC-130 will be monitored and distributed to the other workstations in the EOC. In addition, the manager is responsible for making sure that the aircraft data are transmitted into the AWN. Pertinent aircraft data/information will be passed to the JTWC Duty Forecaster as requested. The manager will ensure that all data under his/her control have been transferred to the TCM-92 Data Manager at the end of each AOP.

(3) **Synoptic Workstation** (one or two people). The Synoptic Manager will be responsible for maintaining working best tracks based on satellite and synoptic fixes for both the tropical cyclone and the MCS. As indicated in Section 4b(1), selected flight-level and dropwindsonde data will be plotted on satellite imagery overlays to facilitate analysis. Based on these analyses, the Synoptic and Satellite Imagery Managers will make aircraft track modification recommendations to the EOC Director. In addition, the Synoptic Manager will maintain forecast tracks for each tropical system based on all available data. Without interfering with the operational function, the Synoptic Manager will work closely with the JTWC forecaster to obtain the tropical cyclone forecast aids, NOGAPS anals and prog charts, current synoptic data, etc. The manager will also make copies of the current gradient/surface and 200 mb analyses, and re-analyze as necessary to reflect new information from the aircraft or satellite imagery. The manager will ensure that all data, charts, forecasts, etc., under his/her control have been transferred to the TCM-92 Data Manager at the end of each AOP mission.

(4) **Data Workstation.** The TCM-92 Data Manager is responsible for collecting and organizing all the raw data collected during each AOP. These data include:

> (*i*) Aircraft data (hard copies from the IWRS groundstation and disks from the aircraft); (*ii*) Paper/film copies of the satellite imagery (Vis and IR/GMS, NOAA and DMSP); (*iii*) Acetates with plotted flight-level and dropwindsonde winds and temperatures at various levels; (*iv*) Magnetic tapes of selected NOAA/DMSP satellite passes: (*v*) Working best tracks of the tropical cyclone and MCS with the plotted fixes; and (*vi*) Copies of JTWC and NOGAPS analyses and forecasts used in the EOC.

The Data Manager will also coordinate the packaging and shipping of these data sets to NPS at the end of TCM-92 for permanent archival.

(5) **Experiment Operations Director.** The Experiment Operations Director has overall responsibility for the TCM-92 field experiment. The Director will chair the meetings of the EOC Team, make assignments for each of the Workstations described above during the AOP, and make the final Go decision for the WC-130 mission, and all the flight-track modifications. The Director will consult with the TCM-92 Project Manager (Professor R. L. Elsberry) and other key scientists as necessary to insure that project objectives are accomplished to the maximum extent possible. In addition, the Director is responsible for maintaining cordial working relationships with the Director, JTWC and Commanding Officer, Naval Oceanography Command Center, Guam.

TABLE 1

TCM92 SCHEDULE DURING 0000 UTC AOP

Guam Time	UTC	Location	Activity
DAY 0			
1200	0200	EXP. OPS CEN	1) Synoptic brief by TCM92 Forecaster (et. al.). 2) Updated status report on aircraft and crew. 3) Open discussion of AOP flight track.
1330	0330	JTWC spaces	JTWC afternoon brief.
1400	**0400**	**EXP. OPS CEN**	**Go decision for 0000 UTC Day 1 AOP. Crew begins crew rest for 1900 UTC take off.**
DAY 1			
0000	1400	EXP. OPS CEN	1) Synoptic brief by the TCM92 Forecaster. 2) Status report on Aircraft and crew. 3) Open discussion of AOP flight track.
0230	**1630**	**EXP. OPS CEN**	**Final Go decision. Crew is alerted. Flight track passed to WC-130 Navigator.**
0400	1800	EXP. OPS CEN	EOC Workstations in operation.
0430	1830	EXP. OPS CEN	Test communications with aircraft.
0500	1900		Aircraft launch for 0000 UTC mission.
1000	0000		Aircraft at MCS Center.
1600	0600		Aircraft recovers.
1600	**0600**	**EXP. OPS CEN**	**Go decision for next 0000 UTC AOP. Crew begins crew rest for 2100 UTC take off.**

TABLE 1 (continued)

DAY 2

Guam Time	UTC	Location	Activity
0200	1600	EXP. OPS CEN	1) Synoptic brief by the TCM92 Forecaster. 2) Status report on Aircraft and crew. 3) Open discussion of AOP flight track.
0430	**1830**	**EXP. OPS CEN**	**Final Go decision. Crew is alerted. Flight track passed to WC-130 Navigator.**
0600	2000	EXP. OPS CEN	EOC Workstations in operation.
0630	2030	EXP. OPS CEN	Test communications with aircraft.
0700	2100		Aircraft launch for 0000 UTC mission.
1200	0200		Aircraft at MCS Center.
1800	0800		Aircraft recovers.
1800	**0800**	**EXP. OPS CEN**	**Go decision for next 0000 UTC AOP. Crew begins crew rest for 2300 UTC take off.**

DAY 3

Guam Time	UTC	Location	Activity
0400	1800	EXP. OPS CEN	1) Synoptic brief by the TCM92 Forecaster. 2) Status report on Aircraft and crew. 3) Open discussion of AOP flight track.
0630	**2030**	**EXP. OPS CEN**	**Final Go decision. Crew is alerted. Flight track passed to WC-130 Navigator.**
0800	2200	EXP. OPS CEN	EOC Workstations in operation.
0830	2230	EXP. OPS CEN	Test communications with aircraft.
0900	2300		Aircraft launch for 0000 UTC mission.
1400	0400		Aircraft at MCS Center.
2000	1000		Aircraft recovers.
2000	**1000**	**EXP. OPS CEN**	**Go decision for next 0000 UTC AOP. Crew begins crew rest for 0100 UTC take off(if desired).**

TABLE 2

TCM92 SCHEDULE FOR 0600 UTC AOP (DIURNAL MIN)

Guam Time	UTC	Location	Activity
DAY 0			
1800	0800	EXP. OPS CEN	1) Synoptic brief by the TCM-92 Forecaster. 2) Status report on Aircraft and crew. 3) Open discussion of desirability of 0600 UTC AOP.
2000	**1000**	**EXP. OPS CEN**	**Go decision for 0600 UTC Day 1 AOP. Aircrew begins crew rest for 0100 UTC takeoff.**
DAY 1			
0600	2000	EXP. OPS CEN	1) Synoptic brief by the TCM92 Forecaster. 2) Status report on Aircraft and crew. 3) Open discussion of AOP flight track.
0730	2130	JTWC Spaces	JTWC morning brief.
0830	**2230**	**EXP. OPS CEN**	**Final Go decision. Crew is alerted.** **Flight track passed to WC-130 Navigator**.
1000	0000	EXP. OPS CEN	EOC Workstations in operation.
1030	0030	EXP. OPS CEN	Test communications with aircraft.
1100	0100		Aircraft launch for 0600 UTC mission.
1600	0600		Aircraft at MCS Center.
2200	1200		Aircraft recovers.
2200	**1200**	**EXP. OPS CEN**	**Go Decision for next 0600 UTC AOP. Crew begins crew rest for 0300 UTC takeoff.**
DAY 2			
0730	2130	JTWC Spaces	JTWC morning brief.
0800	2200	EXP. OPS CEN	1) Synoptic brief by the TCM92 Forecaster. 2) Status report on Aircraft and crew. 3) Open discussion of AOP flight track.
1030	**0030**	**EXP. OPS CEN**	**Final Go decision. Crew is alerted.** **Flight track passed to WC-130 Navigator**.
1200	0200	EXP. OPS CEN	EOC Workstations in operation.

TABLE 2 (Continued

Guam Time	UTC	Location	Activity
1230	0230	EXP. OPS CEN	Test communications with aircraft.
1300	0300		Aircraft launch for 0600 UTC mission.
1800	0800		Aircraft at MCS Center.
0000	1400		Aircraft recovers.
0000	**1400**	**EXP. OPS CEN**	**Go Decision for next 0600 UTC AOP. Crew begins crew rest for 0500 UTC takeoff.**
DAY 3			
0730	2130	JTWC Spaces	JTWC morning brief.
1000	0000	EXP. OPS CEN	1) Synoptic brief by the TCM92 Forecaster. 2) Status report on Aircraft and crew. 3) Open discussion of AOP flight track.
1230	**0230**	**EXP. OPS CEN**	**Final Go decision. Crew is alerted.** **Flight track passed to WC-130 Navigator.**
1400	0400	EXP. OPS CEN	EOC Workstations in operation.
1430	0430	EXP. OPS CEN	Test communications with aircraft.
1500	0500		Aircraft launch for 0600 UTC mission.
2000	1000		Aircraft at MCS Center.
0200	1600		Aircraft recovers.
0200	**1600**	**EXP. OPS CEN**	**Go Decision for next 0600 UTC AOP.** **Crew begins crew rest for 0700 UTC takeoff (if desired).**

TABLE 3

TCM92 SCHEDULE DURING 1200 UTC AOP

Guam Time	Time	Location	Activity
DAY 0			
0000	1400	EXP. OPS CEN	1) Synoptic brief by TCM92 Forecaster. 2) Updated status report on aircraft and crew. 3) Open discussion of AOP flight track.
0200	**1600**	**EXP. OPS CEN**	**Go decision for 1200 UTC Day 1 AOP. Crew begins crew rest for 0700 UTC takeoff.**
DAY 1			
1200	1200	EXP. OPS CEN	1) Synoptic brief by TCM92 Forecaster. 2) Updated status report on aircraft and crew. 3) Open discussion of AOP flight track.
1330	0430	JTWC spaces	JTWC afternoon brief.
1430	**0430**		**Final Go decision. Crew is alerted. Flight track passed to WC-130 Navigator.**
1600	0600	EXP. OPS CEN	EOC workstations in operation.
1630	0630	EXP. OPS CEN	Test communications with aircraft.
1700	0700		Aircraft launch for 1200 UTC mission.
2200	2000		Aircraft at MCS Center.
0400	1800		Aircraft recovers.
0400	**1800**	**EXP. OPS CEN**	**Go decision for next 1200 UTC AOP. Crew begins crew rest for 0900 UTC take off.**
DAY 2			
1400	0400	EXP. OPS CEN	1) Synoptic brief by TCM92 Forecaster. 2) Updated status report on aircraft and crew. 3) Open discussion of AOP flight track.
1530	0530	JTWC spaces	JTWC afternoon brief.
1630	**0630**	**EXP. OPS CEN**	**Final Go decision. Crew is alerted. Flight track passed to WC-130 Navigator.**
1800	0800	EXP. OPS CEN	EOC workstations in operation.
1830	0830	EXP. OPS CEN	Test communications with aircraft.

TABLE 3 (Continued)

Guam Time	**Time**	**Location**	**Activity**
1900	0900		Aircraft launch for 1200 UTC mission.
0000	1400		Aircraft at MCS Center.
0600	2000		Aircraft recovers.
0600	**2000**	**EXP. OPS CEN**	**Go decision for next 1200 UTC AOP. Crew begins crew rest for 1100 UTC take off.**
DAY 3			
1600	0600	EXP. OPS CEN	1) Synoptic brief by TCM92 Forecaster. 2) Updated status report on aircraft and crew. 3) Open discussion of AOP flight track.
1830	**0830**	**EXP. OPS CEN**	**Final Go decision. Crew is alerted. Flight track passed to WC-130 Navigator.**
2000	1000	EXP. OPS CEN	EOC workstations in operation.
2030	1030	EXP. OPS CEN	Test communications with aircraft.
2100	1100		Aircraft launch for 1200 UTC mission.
0200	1600		Aircraft at MCS Center.
0800	2200		Aircraft recovers.
0800	**2200**	**EXP. OPS CEN**	**Go decision for next 1200 UTC AOP. Crew begins crew rest for 1100 UTC take off.**

TABLE 4

TCM92 SCHEDULE DURING 1800 UTC AOP (DIURNAL MAX)

Guam Time	UTC	Location	Activity
DAY 0			
0600	2000	EXP. OPS CEN	1) Synoptic brief by the TCM92 Forecaster. 2) Status report on Aircraft and crew. 3) Open discussion of AOP flight track.
0815	2215	JTWC Spaces	JTWC morning brief.
0800	**2200**	**EXP. OPS CEN**	**Go decision for 1800 UTC AOP. Crew begins crew rest for 1800 UTC takeoff.**
DAY 1			
1800	0800	EXP. OPS CEN	1) Synoptic brief by the TCM92 Forecaster. 2) Status report on Aircraft and crew. 3) Open discussion of AOP flight track.
2030	**1030**	**EXP. OPS CEN**	**Final Go decision. Crew is alerted. Flight track passed to WC-130 Navigator.**
2200	1200	EXP. OPS CEN	EOC workstations in operation.
2230	1230	EXP. OPS CEN	Test communications with aircraft.
2300	1300		Aircraft launch for 1800 UTC mission.
0400	1800		Aircraft at MCS Center.
1000	0000		Aircraft recovers.
1000	0000	**EXP. OPS CEN**	**Go decision for next 1800 UTC AOP. Crew begins crew rest for 1500 UTC take off.**
DAY 2			
2000	1000	EXP. OPS CEN	1) Synoptic brief by the TCM92 Forecaster. 2) Status report on Aircraft and crew. 3) Open discussion of AOP flight track.
2230	**1230**	**EXP. OPS CEN**	**Final Go decision. Crew is alerted. Flight track passed to WC-130 Navigator.**
0000	1400	EXP. OPS CEN	EOC workstations in operation.
0030	1430	EXP. OPS CEN	Test communications with aircraft.

TABLE 4 (Continued)

Guam Time	**UTC**	**Location**	**Activity**
0100	1500		Aircraft launch for 1800 UTC mission.
0600	2000		Aircraft at MCS Center.
1200	0200		Aircraft recovers.
1200	0200	EXP. OPS CEN	**Go decision for next 1800 UTC AOP. Crew begins crew rest for 1700 UTC take off.**
DAY 3			
2200	1200	EXP. OPS CEN	1) Synoptic brief by the TCM92 Forecaster 2) Status report on Aircraft and crew. 3) Open discussion of AOP flight track.
0030	**1430**	**EXP. OPS CEN**	**Final Go decision. Crew is alerted. Flight track passed to WC-130 Navigator.**
0200	1600	EXP. OPS CEN	EOC workstations in operation.
0230	1630	EXP. OPS CEN	Test communications with aircraft.
0300	1700		Aircraft launch for 1800 UTC mission.
0800	2200		Aircraft at MCS Center.
1400	0400		Aircraft recovers.
1400	**0400**	**EXP. OPS CEN**	**Go decision for next 1800 UTC AOP. Crew begins crew rest for 1900 UTC take off (if desired).**

APPENDIX: Flight Tracks

Track 1: Guam -> MCS -> TC -> MCS -> Guam (Fig. A-1)
Distance: 2926 n mi Time: 11 hrs 18 min
MCS is 540 n mi straight line distance from Guam
TC is 750 n mi from Guam

- Track is flown such that first penetration (Fig. A-1a) of MCS is at FL 180 - FL 200, True Air Speed (TAS) - 250 kt.

- Sondes are released every 55 n mi (100 km), or as close to this distance as possible. If spacing must be increased, drops in the center of the MCS will be deleted and subsequent respacing of dropsondes accomplished.

- Track between MCS and TC will be at same FL and dropsonde spacing.

- Track through TC will be only one south to north track with sonde spacing every 65 n mi due to the distance of the TC from Guam. The inbound and outbound legs are 130 n mi. FL 180 - FL 200, TAS 250 kt will be maintained unless safety considerations require penetration at FL 100, TAS 220 kt. If sonde spacing is difficult, then only two drops need be made, these would include those on either side of the TC center outside the maximum wind band (see Fig. A-1a).

- Upon completion of TC track, climb will be made to FL 300, TAS 270 kt, enroute to MCS. Dropsonde will be launched upon reaching this altitude. Subsequent drops will occur as close to 100 n mi (185 km) spacing as possible.

- Second penetration track of MCS will be made with axes of alpha pattern 45^0 offset from those of the first track (see Fig. A-1b). FL 300 will be maintained. FL 340 may be requested when or if possible. Sonde spacing is same as above.

NOTES:

(1) Large circles on figures denote TC and MCS storm areas. Each is approximately 4° lat. in diameter, but this may change depending on individual storms.
(2) Flight tracks are based on no ATC restrictions.
(3) Distance between MCS and TC is -4° lat., this obviously may vary.
(4) RECCO observations will be made with each drop.
(5) Flight-level altitudes do not need to be at standard pressure levels, so that flight levels may be changed as each mission progresses.
(6) Outbound and inbound tracks to and from storm areas will be at flight levels and air speeds that minimize fuel consumption.

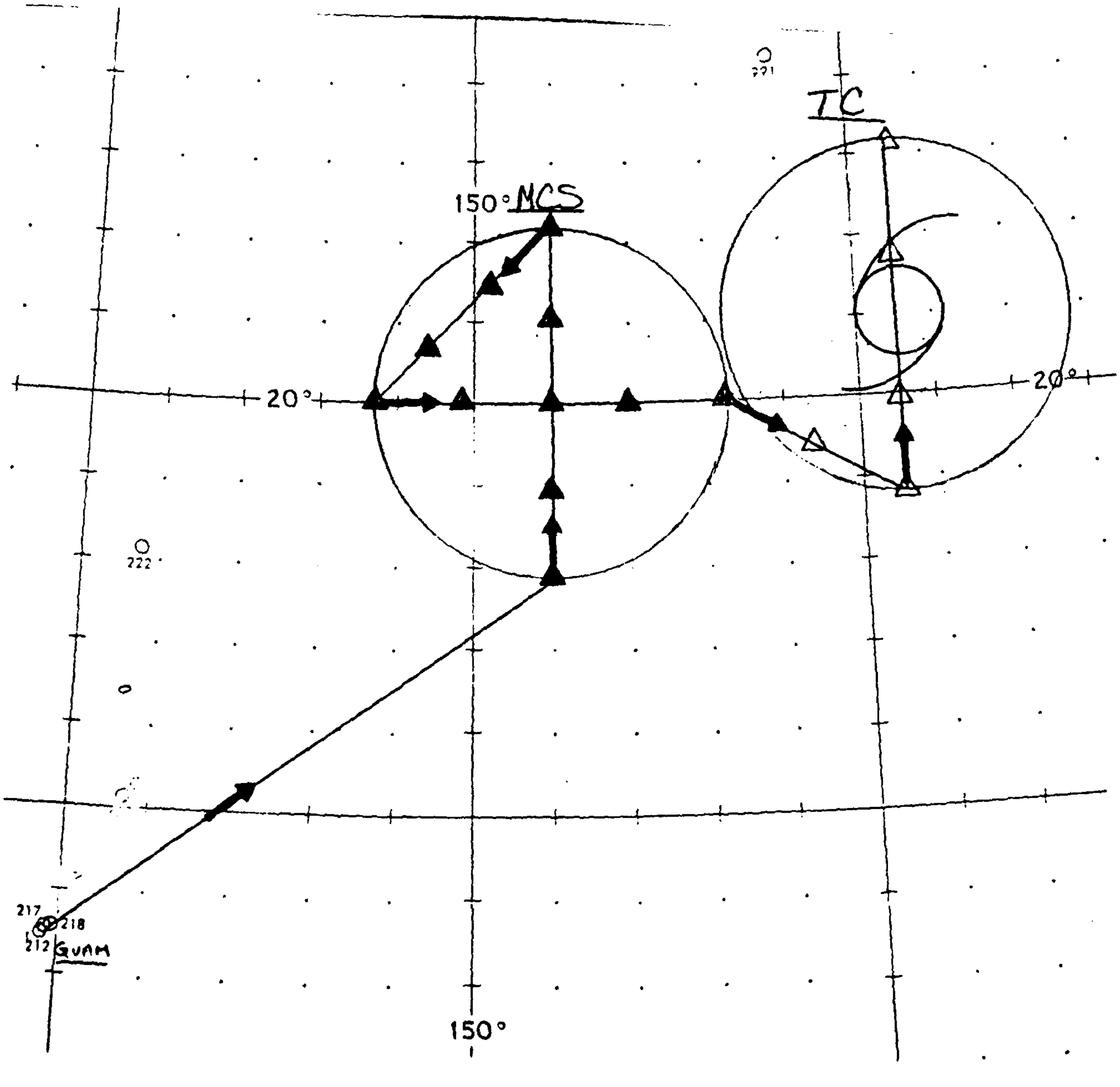

Fig. A-1a Outbound leg of Track 1 from Guam with filled (open) triangle symbols for dropwindsonde locations in the MCS (tropical cyclone).

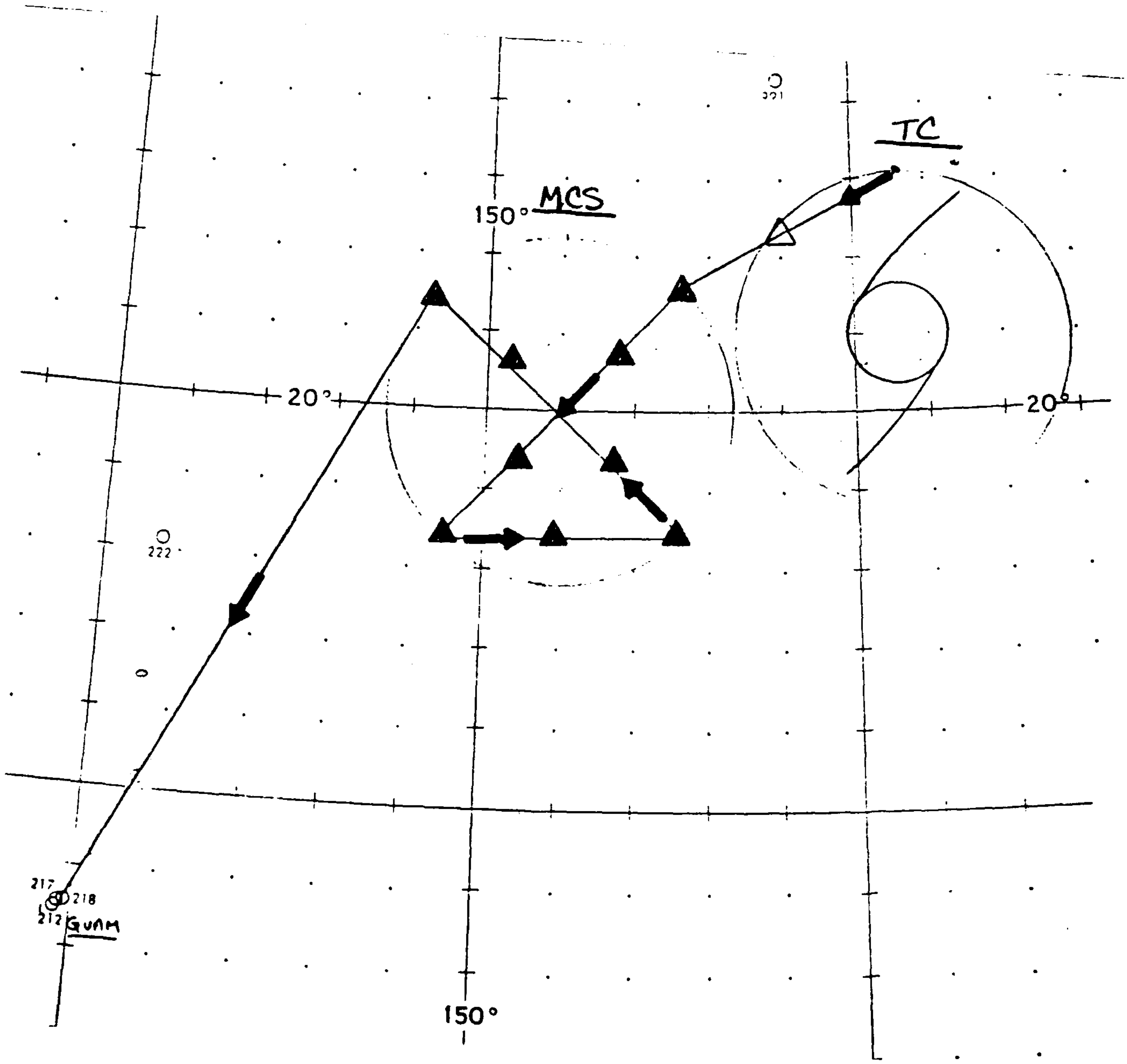

Fig. A-1b Return leg of Track 1.

APPENDIX: Flight Tracks

Track 2: Guam -> TC -> MCS -> Kadena (Fig. A-2)

- This track allows for possibility of TC/MCS being too far from Guam to fly roundtrip.

- In this case, TC is flown first at FL 180 - FL 200, TAS 250 kt. Sonde spacing is as with Track 1, as close to 65 n mi as possible. No drops in center. Again, if safety requires, FL 100 will be flown.

- Track between TC and MCS will be at FL 180 - FL 200, TAS 250 kt. Sonde Spacing will be as close to 55 n mi spacing as possible.

NOTES: Same notes apply as in Track 1.

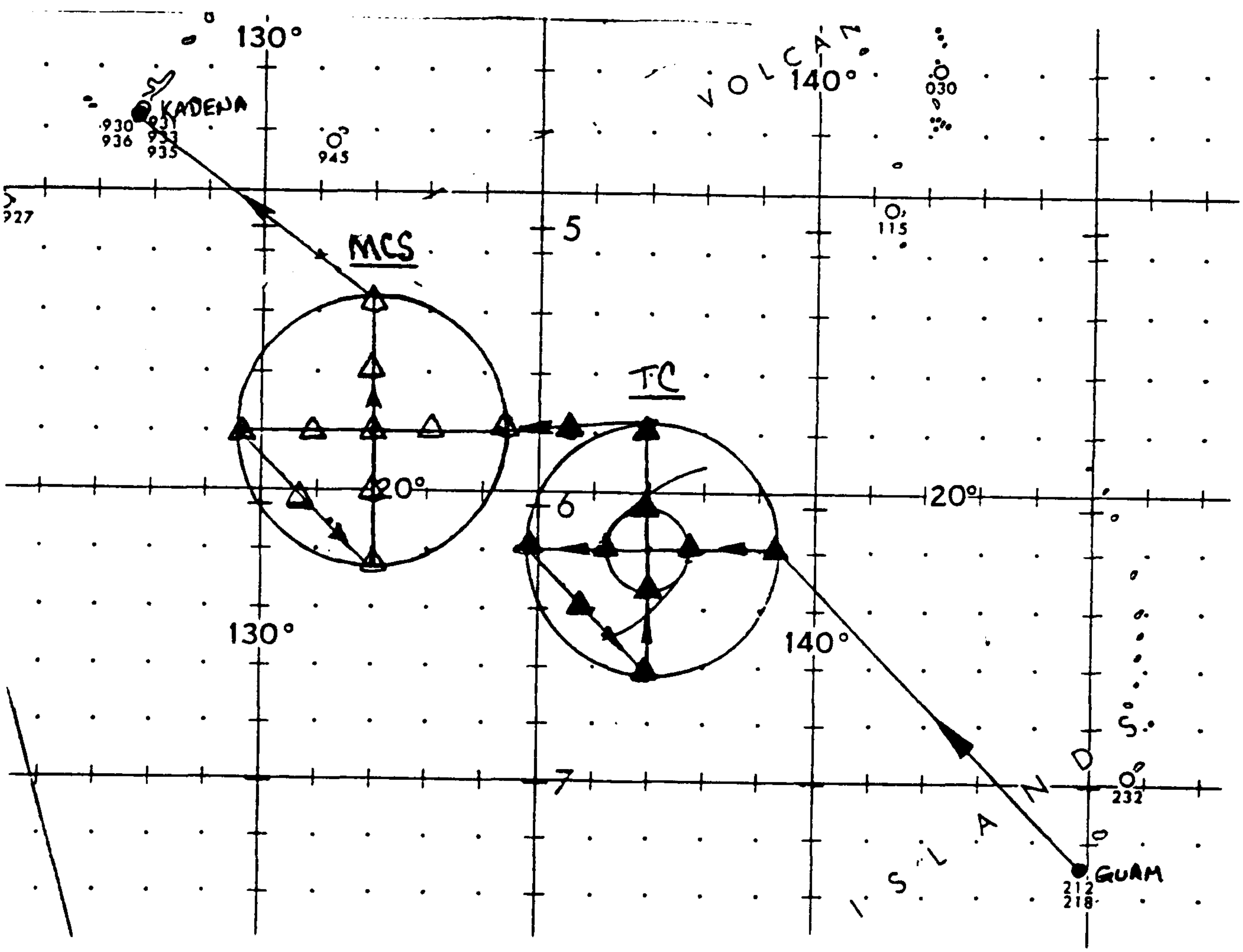

Fig. A-2 As in Fig. A-1, except for Track 2 with recovery at Kadena AB, Okinawa.

APPENDIX: Flight Tracks

Track 3: Guam -> MCS -> Guam (Fig. A-3)
Distance: ~ 3000 n mi Total Time: ~ 12 hrs

- This track is for a mission to document the structure of a MCS in the vicinity of Guam prior to the TC formation. This mission will provide valuable data if three levels could be flown through the MCS. If the MCS contains a convective rainband or line of convergence extending from its circulation center, then cross-tracks through it will be flown. Strong convective cells can be avoided for safety considerations.

- As shown in Fig. A-3a, a FL 100 track would be flown first. Upon reaching 60 - 90 n mi of the forecast position of the circulation center, an inbound leg, west to east in this case, would be flown in an attempt to fix the center. If upon reaching the forecast center, a fix can not be made, the TCM-92 Chief Aircraft Scientist may request that further efforts be made to find the center of circulation. Most likely, the outbound leg will be continued along the west-east course.

- At a distance of 60 - 90 n mi from the forecast (or fixed) center, an outward 360^o "spiral" will be flown with the wind. Spiral will be flown at FL 100 extending southward, in this case, in order to fly the rainband. Upon completion of rainband cross-tracks, a climb to FL 180 - 200 is initiated such that upon reaching this altitude, an alpha pattern is flown starting at the due east position of the MCS (Fig. A-3b).

- Fig. A-3b shows the FL 180 - FL 200 alpha pattern with the same Dropsonde spacing and airspeed as in Tracks 1 and 2. Climb to FL 300 will be accomplished along second cross-track.

- Fig. A-3c shows the FL 300 alpha pattern rotated 45^0 from the FL 180 - 200 alpha pattern with an additional cross-track after second inbound/outbound leg. Sonde spacing shows 4 drops per inbound/outbound leg. This will only be possible if the MCS area is enlarged to ~ 600 km in diameter. Otherwise, drops will be made as per Tracks 1 and 2.

NOTES: Notes of Track 1 also apply.

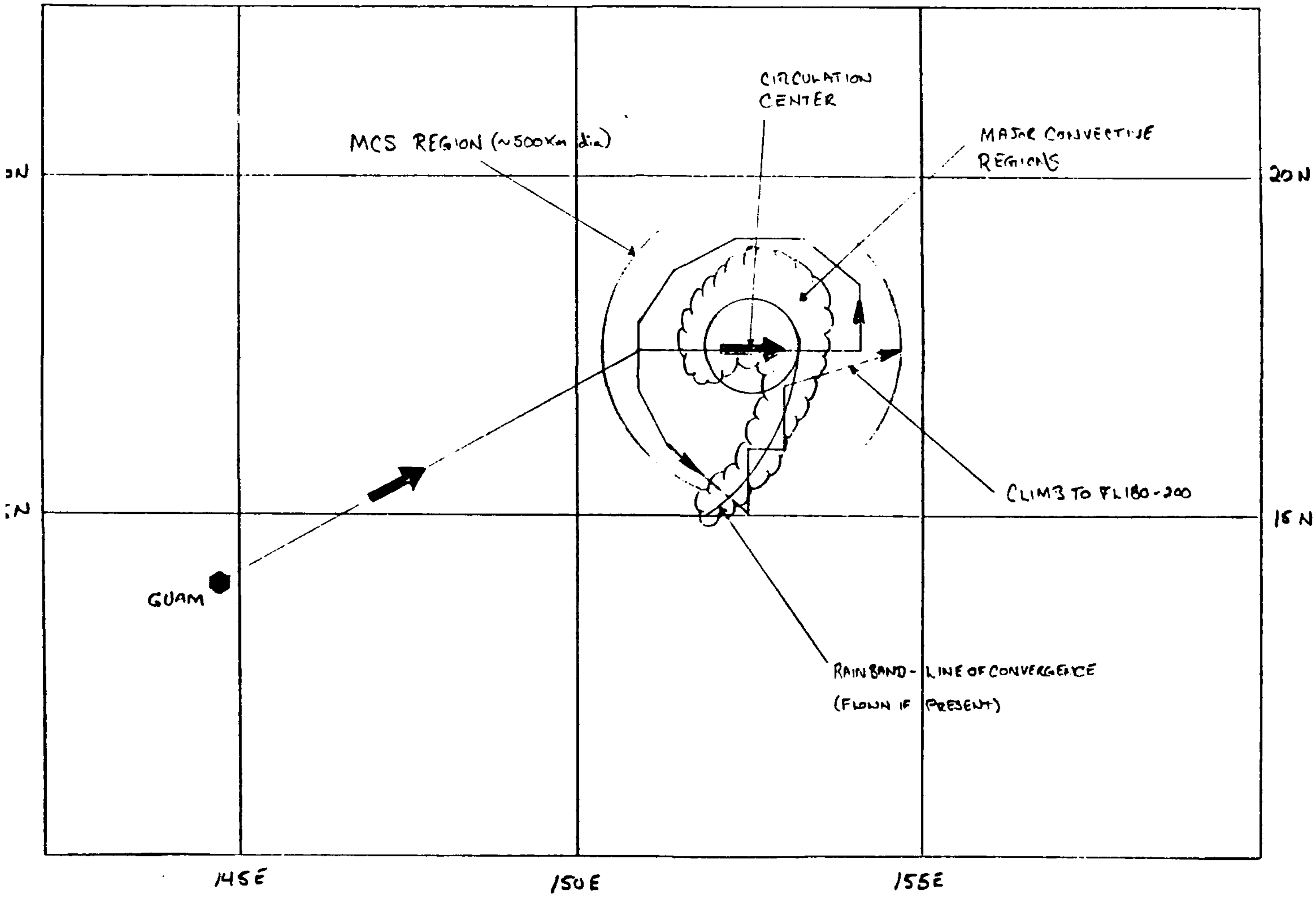

Fig. A-3a As in Fig. A-1, except for Track 3 first penetration at 10,000 ft of an isolated MCS without dropwindsondes.

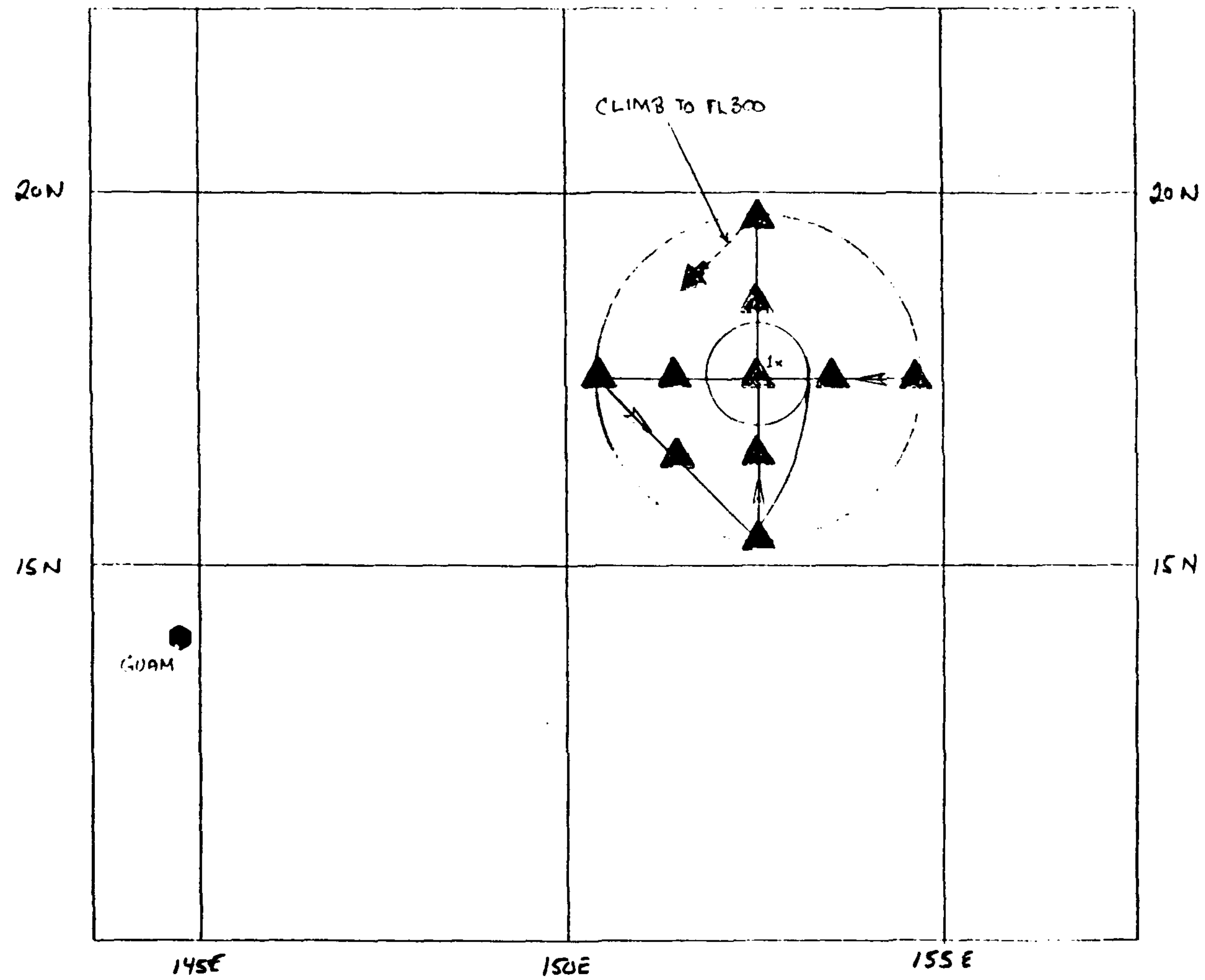

Fig. A-3b As in Fig. A-1, except for Track 3 second penetration at 18,000 - 20,000 ft with dropwindsondes.

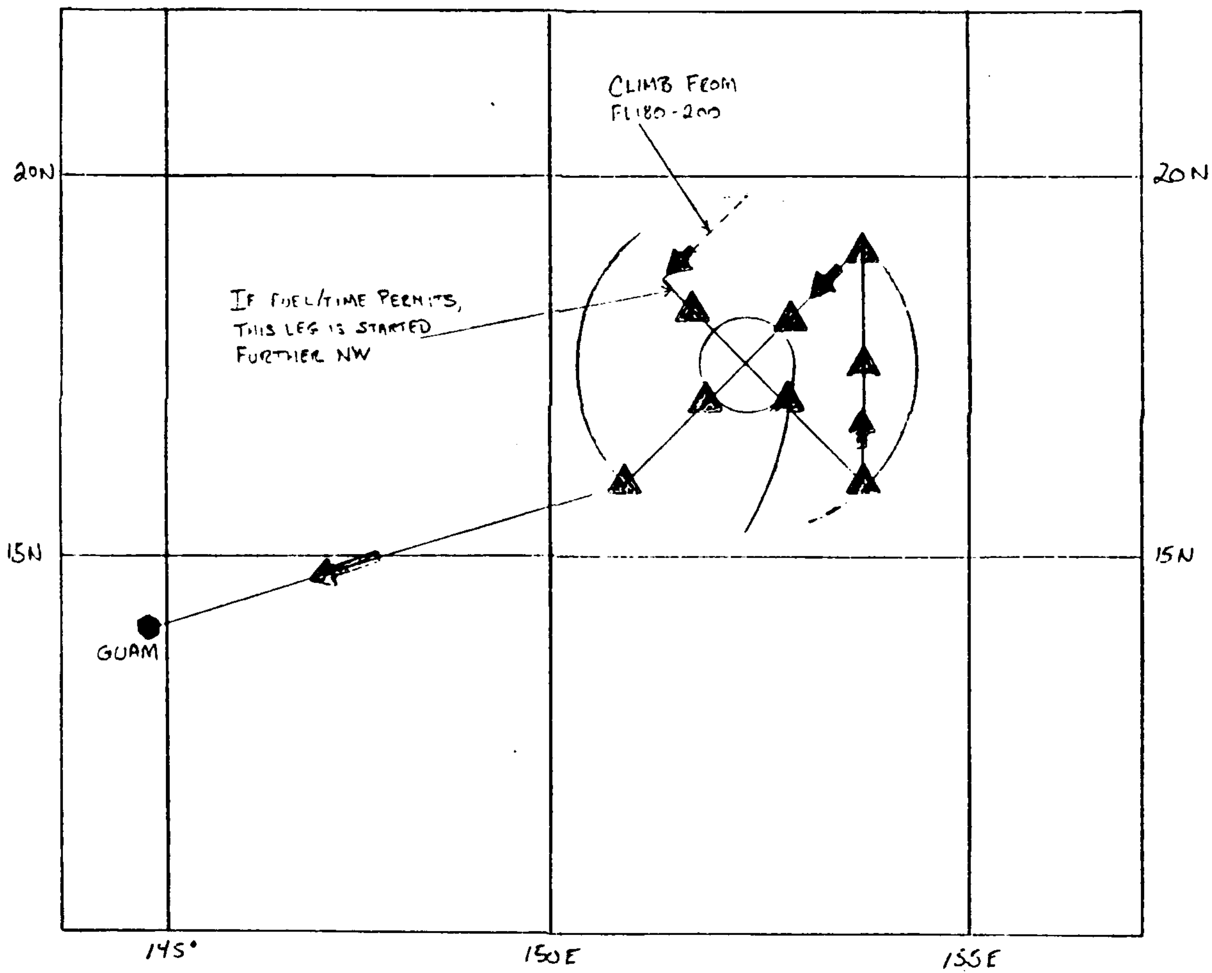

Fig. A-3c As in Fig. A-1, except for Track 3 third penetration at 30,000 ft with dropwindsondes.

REFERENCES

Black, P. G., 1977: Some aspects of tropical storm structure revealed by hand-held camera photographs from space. Skylab Explores the Earth, NASA SP-380, Government Printing Office, Washington, DC, 417-462.

Elsberry, R. L., 1987: Tropical cyclone motion. Chapter 4, A Global View of Tropical Cyclones, Office of Naval Research, 91-131.

Elsberry, R. L., 1990: International experiments to study tropical cyclones in the western North Pacific. Bull. Amer. Meteor. Soc., 71, 1305-1316.

Elsberry, R. L., *et al.*, 1990: ONR Tropical Cyclone Research Initiative: Field experiment and summary. Tech. Report NPS-MR-91-001, Naval Postgraduate School, Monterey, CA 93943, 106 pp.

Elsberry, R. L., and R. F. Abbey, Jr., 1991: Recent advances in understanding tropical cyclone motion. Tech. Report NPS-MR-92-001, Naval Postgraduate School, Monterey, CA 93943, 92 pp.

Fett, R. W., and S. Brand, 1975: Tropical cyclone movement forecasts based on observations from satellites. J. Appl. Meteor., 452-456.

Flatau, M., 1991: The role of baroclinic processes in tropical cyclone motion. *Preprints*, 19th Conference on Hurricanes and Tropical Meteorology, Miami, FL, American Meteorological Society, Boston, MA, 349-352.

Frank, W. M., 1992: Tropical cyclone formation. Colorado State University, Department of Atmospheric Sciences, 30th Anniversary Symposium, 5-6 May.

Frank, W. M., and Shuyi Chen, 1991: Simulations of vortex formation in convective weather systems. *Preprints*, 19th Conference on Hurricanes and Tropical Cyclones, Miami, FL, American Meteorological Society, Boston, MA, 241-244.

Fritsch, J. M., 1992: Warm-core vortex amplification over land. Colorado State University, Department of Atmospheric Sciences, 30th Anniversary Symposium, 5-6 May.

Harr, P. A., T. Neta, and R. L. Elsberry, 1991: ONR Tropical Cyclone Motion Research Initiative: Data user's guide to observations. Tech. Report NPS-MR-91-002, Naval Postgraduate School, Monterey, CA 93943, 123 pp.

Hertenstein, R. F. A., and W. H. Schubert, 1991: Potential vorticity anomalies associated with squall lines. Mon. Wea. Rev., 119, 1663-1672.

Holland, G. J., 1992: So what makes a hurricane: Formation and development. Colorado State University, Department of Atmospheric Sciences, 30th Anniversary Symposium, 5-6 May.

Holland, G. J., and M. Lander, 1991: On the meandering nature of tropical cyclones. J. Atmos. Sci., (submitted).

Lajoie, F. A., and N. Nicholas, 1974: A relationship between the direction of movement of tropical cyclones and the structure of their cloud systems. Tech. Report No. 11, Bureau of Meteorology, Melbourne, Australia, 22 pp.

Maddox, R. A., 1980: Mesoscale convective complexes. Bull. Amer. Meteor. Soc., **61**, 1374-1387.

Raymond, D. J., and H. Jiang, 1990: A theory for long-lived mesoscale convective systems. J. Atmos. Sci., **47**, 3067-3077.

Willoughby, H. E., 1991: Linear motion of a shallow-water barotropic vortex as an initial value problem. J. Atmos. Sci., (submitted).

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